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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

DEPARTMENT OF RADIO ELECTRONICS

ÚSTAV RADIOELEKTRONIKY

DESIGN OF RC SINUSOIDAL OSCILLATOR BASED ON ACTIVE BUILDING BLOCKS

NÁVRH RC SINUSOVÉHO OSCILÁTORU S AKTIVNÍMI FUNKČNÍMI BLOKY

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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VEDOUCÍ PRÁCE

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FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní obor **Elektronika a sdělovací technika**
Ústav radioelektroniky

Student: Patrik Režňák ***ID:*** 173733
Ročník: 3 ***Akademický rok:*** 2016/17

NÁZEV TÉMATU:

Návrh RC sinusového oscilátoru s aktivními funkčními bloky

POKYNY PRO VYPRACOVÁNÍ:

Seznamte se principy RC oscilátorů s aktivními funkčními bloky a proveďte srovnávací studii možností použití různých jejich typů. Po konzultaci s vedoucím práce vyberte vhodné aktivní funkční bloky, navrhněte obvodová zapojení sinusových oscilátorů a simulujte jejich vlastnosti v OrCAD PSpice.

Proveďte rešerši komerčně dostupných funkčních bloků pro implementaci oscilátorů v laboratorním přípravku. Navrhněte desku plošných spojů v Eagle, proveďte konstrukci laboratorního přípravku a měření vlastností navržených oscilátorů. Naměřené výsledky srovnejte s výsledky počítačových simulací.

DOPORUČENÁ LITERATURA:

[1] PUNČOCHÁŘ, J. Operační zesilovače v elektronice. Praha: BEN – technická literatura, 2002.

[2] GOTTLEIB, I. M. Practical Oscillator Handbook. Oxford: Newnes, 1997.

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ABSTRAKT

Bakalárska práca je venovaná RC oscilátorom s použitím funkčných blokov a operačných zosilovačov. Na počiatku je urobený rešerš literatúry zaoberajúcej sa konštrukciou a návrhom RC oscilátorov, a použitiu rôznych funkčných blokov pri tomto návrhu. Jednotlivé funkčné bloky sú diskutované a sú vybrané rôzne zapojenia s použitím týchto blokov, ktoré sú simulované analýzou na počítači pomocou PSpice a SNAP. Je overený vznik oscilácií a vplyv jednotlivých súčiastok v zapojení. V druhej časti sú realizované vybrané zapojenia a overené teoretické poznatky na praktickej realizácii. Údaje získané z počítačovej simulácie a praktickej realizácie sú potom porovnané, a taktiež jednotlivé zapojenia sú porovnané medzi sebou.

KĽÚČOVÉ SLOVÁ

RC oscilátor, operačný zosilovač s prúdovou spätnou väzbou, simulácia, funkčné bloky, konvejor, návrh, vlastnosti.

ABSTRACT

Thesis is focused on RC oscillators employing active building blocks and operational amplifiers. In the beginning, review of available literature talking about this topic is done. Different building blocks and circuits containing those blocks are picked and some of them simulated with PSpice and SNAP programs. Oscillation creation and influence of circuit components is verified. Those circuits are realized in practical application and simulation results are compared to those gained from real world circuits, also the chosen circuits are compared between each other.

KEYWORDS

RC oscillator, current feedback operational amplifier, simulation, active building blocks, conveyor, design, parameters.

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DECLARATION

I declare that I have made my Bachelor’s Thesis, with the subject of Design of RC oscillator with active function blocks, independently, under supervision of my supervisor Mgr. Aslihan Kartci, using the technical literature and the other information sources which are all cited in the text and enumerated in the list of the references at the end of this thesis.

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V Brně dne ....

(podpis autora)

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INTRODUCTION

Sinusoidal oscillators play an important role in communication, measurement, computing and control systems. There are many applications in electronic, communication systems and automation systems where square wave, sine wave, triangle wave or saw wave forms are used or required. In most cases it is necessary to use more than one type of signal. This requires the production of a signals suitable for the desired operation. This signals are generated by oscillators.

Oscillators may be used in signal generators, A/D and D/A converters, spectrum analysers, for biomedical applications and many more. The first electrical oscillators worked on mechanical principle and was not able to produce high frequency signals. Smaller, more effective and precise oscillators were created with the invention of vacuum tube and transistor. In the early 60. of the last century more and more operational amplifiers were created and being used as the main part in creation of RC sinusoidal oscillators, as time went by, several alternative building blocks for analog circuit design were created, each offering different advantages and disadvantages. Today most popular building blocks for RC oscillator design are Current conveyors (CC), Operation transresistance amplifier (OTRA), Current differencing buffered amplifier (CDBA), Four terminal floating nullor (FTFN), Operational transconductance amplifier (OTA).

In this thesis, review of available literature talking about RC oscillators with building blocks is done. Then some interesting circuits are picked and the main goal is simulation and practical realization with intention to compare different blocks, and different circuits, by computer simulation and real world realization.

1. OBJECTIVE OF THE THESIS

RC oscillators were usually used for low frequency and LC oscillators for high frequency applications, however with time and better technology the RC oscillators provided better characteristic and wider bandwidth. Today there is a lot of requirements for RC oscillators and one of them is easy implementation and integrated circuit fabrication with preservation of the circuit preferences. There are many kinds of building block suitable for oscillator use and the main intention of this thesis is to pick up some of those blocks, talk about them, create a simulation for circuits employing those blocks and realize those circuits as circuit board. Generally talking, a circuit employing minimum number of active and passive components is wanted because of better integration, cost and power consumption.

This thesis is divided into several parts, from beginning it is focused on general talk about oscillators, building blocks, its description and older publications review. Then some interesting circuits are picked, simulated and circuit boards are produced. Those circuits are measured and the results are compared to the simulation results.

As first, oscillator circuit presented by Abuelma'ati in 2010, with two CFOAs is picked, simulated and measured on breadboard and PCB variation.

A current differencing buffed amplifier (CDBA) based oscillator circuit presented by Acar and Ozoguz in 1998 is chosen as second oscillator. This circuit is also analysed, simulated and measured on breadboard and PCB and results of those measurements are compared.

1.1 Literature review

This article is focused on different studies related to RC oscillator circuits from the early 90s until year 2010.

1979, Senani Presented new single resistance controlled sine oscillator, it features single CCII and independent control of the oscillations thru single grounded resistor without affecting the oscillation condition [1].

1990, Abuelma'ati Presented transconductance-amplifier-capacitor sine oscillator requiring only two OTAs and two grounded capacitors, while frequency is linearly tuneable over a wide range and circuit is attractive for IC realization where the effect of stray capacitances can be minimalized [2].

1991, Vosper Presented first order active R oscillator is which uses two cascade all-pass networks. Equal-amplitude quadrature outputs are available, and the oscillation frequency is controlled thru pair of equal grounded resistors, which makes it useful for electronic frequency variation or digital programing via programmable resistor arrays. Performance of the circuit is close to an ideal quadrature oscillator [3].

1993, Bhaskar and Senani Presented CC Based minimum component oscillator which provides non-interacting control of oscillation frequency through a single grounded resistor, easy convertibility into voltage-controlled oscillator, use of two grounded capacitors which makes it suitable for IC implementation, availability of buffered output and very good frequency stability in contrast to minimum-component SRCOs proposed elsewhere [4].

1994, Senani Presented study of equivalent forms of single op-amp sinusoidal RC oscillators. It is known that single op-amp oscillators have four equivalent stable forms when op-amp is represented by nullor and when nullor is replaced back as DIGO op-amp. When the nullor is looked upon as FTFN, he number of equivalent realizations are much more than four. These realizations have some interesting properties not available in the known four equivalent forms [5].

1995, Wu et al. Presented a multiphase sinusoidal oscillator circuit using the CFOA. Three CFOAs and six resistors were used in the circuit. As a capacity element, the parasitic capacities of the CFOA have been utilized. Voltage controlled phase oscillator can be realized if each phase has a voltage controlled grounded capacitor [6].

1996, Liu and Liao Presented a current mode quadrature sinusoidal oscillator using single FTFN which provides controllable frequency thanks to grounded resistor, is easily converted into voltage controlled oscillator, and suitable for IC implementation and have low passive and active sensitivities [7].

1996, Senani and Singh Presented a sinusoidal oscillator circuit that can control the oscillation frequency with a single resistance using two CFOA active elements, two grounded capacitors and three resistors. the commercially produced AD844 integrated CFOA was used as an element and experimental work was carried out. It has also been shown that the RC oscillator can be achieved without the use of an external capacitor by using the parasitic capacitors of the AD844 [8].

1997, Martinez et al. Presented a sinusoidal oscillator circuit using AD844. In this circuit, the oscillation frequency and the oscillation condition can be controlled independently by two grounded resistors [9].

1997, Horng et al. Presented four single passive element controlled sinusoidal oscillator circuits using the CCII model. These circuits use two CCII, two capacitors and two resistors. The main features are use of minimum number of passive elements and independent control by grounded passive elements [10].

1998, Abuelma’ati and Al-zaher Presented active only sinusoidal oscillator circuit using only active elements of two Op-amps and three OTA without any passive elements [11].

1998, Cam et al. Presented six different OTA-C oscillators. Using only four or five OTAs. The oscillation frequencies are controlled by transient conductivity of the OTA and the oscillation condition is not affected [12].

1998, Abuelma'ati and Qahtani Presented a multiphase sinusoidal oscillator circuit using the CCII. The proposed structure can be configured to produce an even-number or an odd-number of equal-amplitude equally spaced in-phase output currents. This structure enjoys the feature that all capacities in the circuit are grounded [13].

1998, Kuntman and Ozpinar Presented nine different oscillator circuits using the DO-OTA. There are only two grounded capacities in the circuits and high output voltage amplitudes [14].

1999, Abuelma'ati and Alzaher Presented a current-mode sinusoidal oscillator circuit using a single FTFN. A number of current-mode sinusoidal oscillator circuits is presented, each uses one FTFN and, at most eight passive elements [15].

1999, Acar and Ozoguz Presented a new multi-terminal active component with two inputs and two outputs called current differencing amplifier derived from commercially available CFA [16]

2000, Ozcan et al. Presented new oscillator circuits using CDBA. The main advantage of this circuits is low output resistance at terminal w. And the topologies employ a reduced number of passive elements, namely two capacitors and three resistors. Frequency can be controlled by a single grounded resistor [17].

2000, Toker et al. Presented a new circuits realizing first-order canonical current processing all-ass filters based on CDBA. Those circuits are cascadable thanks to their high output impedances and use fewer active and passive components as the previously reported circuits [18].

2000, Tao and Fidler Presented a method of sinusoidal oscillators and second order filters synthesis using OTA. With this method, two grounded capacitors, two OTAs and a small number of resistors were used to create oscillator and filter circuits [19].

2001, Horng Presented two new sinusoidal oscillator circuits using two CCIIs. In the first proposed circuit, there are two CCIIs, two resistors and two grounded capacitors. In the second circuit, the different structure is achieved and the electrical oscillation frequency adjustment is achieved [20].

2002, Toker et al. Presented new oscillator implementations using a single current feedback op-amp. Four new oscillator circuits have been obtained. The frequency stability of the circuits has been examined and it has been discovered that some of those circuits are suitable for high frequency applications [21].

2002, Cam Presented a new oscillator circuit which uses the OTRA as active element and the oscillation frequency can be adjusted thru a single resistor. In this circuit an OTRA, two capacitors and three resistors are used [22].

2002, Prommee and Dejhan Presented quadrature sinusoidal oscillator using CMOS OTA. The experimental results are confirmed by PSpice and the highest oscillating frequency is about 2MHz [23].

2002, Guneş and Toker Presented an improved method of oscillator circuit synthesis using state variable technique and block diagrams. Using this method, a single resistance-controlled oscillator circuit was created using a CFOA. Then a new active element called DVCFA (Differential Voltage Current Feedback Amplifier) was introduced and a new, single-resistor-controlled oscillator circuits are presented. Finally, PSPICE simulations of the circuits and experimental works have been performed [24].

2003, Kumwachara and Surakampontorn Presented an integrable temperature-insensitive gm-RC quadrature oscillator. Main features of this oscillator are the oscillation frequency independency to ambient temperature and all passive elements are grounded. The oscillation frequency can be electronically tuned without disturbing the condition of oscillation [25].

2004, Keskin Presented oscillator circuits designed with Negative impedance components. The designed circuits contain CCII, CDBA, OTRA and operation amplifier. All of those circuits enjoy small component sensitivities [26].

2005, Galan et al. Presented new voltage controlled sinusoidal oscillator using OTA containing MOS transistors. The proposed OTA structure has low power consumption. Experimental work has been carried out and the OTA's transconductance has high linearity and can be adjusted over a wide range [27].

2005, Bhaskar and Senani Presented a new single resistance controlled oscillator using two FTFN. The circuit feature very good frequency stability, low active and passive sensitivities and independent single grounded resistor oscillation frequency control [28].

2005, Gupta and Senani Presented a new active building block called DDCCFA (Differential Difference Complementary Current Feedback Amplifier). Using this block, they have presented SRCO employing grounded capacitors. The new circuit possess features that have not been available simultaneously in any known SRCO before. The simulation results were verified by practical implementation [29].

2005, Khan et al. presented a sinusoidal RC oscillator circuit using CCII+. The oscillation condition and the oscillation frequency can be controlled independently of each other. The AD844 was used and experimental results conformed well with the simulations [30].

2006, Horng et al. Presented first-order all-pass filter circuit using one DDCC, one grounded capacitor and two free resistors. Based on this all-pass filter circuit, they have obtained quadrature oscillator and even-phase sinusoidal oscillators [31].

2006, Fongsamut et al. Presented a new sinusoidal oscillator circuit using two

CCIIs, two grounded capacitors, and two resistors. The oscillator provided good frequency stability and experimental work was carried out [32].

2006, Keskin and Biolek Presented a new current-driven quadrature oscillator circuit using the CDTA. The circuit features high impedance output terminals, has no floating capacitors and the frequency can be electrically controlled [33].

2006, Bhaskar and Senani Presented a new CFOA based sinusoidal oscillator circuits. With use of two CFOAs and five passive elements, eight single-resistor-controlled oscillator circuits and three voltage-controlled oscillator circuits were presented. Experimental results based upon AD844-type CFOA were made, which confirm the practical workability of the new circuits [34].

2008, Tangsrirat et el. Presented a new simple current-controlled multiphase sinusoidal oscillator circuit using the CDTA. In the proposed circuit employs only one CDTA and grounded capacitor for each phase. The oscillation frequency and the oscillation condition can be controlled independently of each other [35].

2008, Tangsrirat et al. Presented quadrature oscillator circuit, which can be controlled with a single resistor using the CDBA. In comparison with the previously reported circuits, the proposed configuration considerably reduces the number of passive elements [36].

2008, Tanaphatsiri et al. Presented a first-order all-pass filter circuit was implemented using a current-controlled CDTA. The application example as a quadrature oscillator is given. The pole frequency can be controlled electronically via the input bias current [37].

2009, Souliotis and Psychalinos Presented a current-mode multiphase oscillator circuit using current amplifier circuit implemented with MOS transistors. The current outputs have high impedance and circuit uses a current amplifier for each phase output. The proposed topology has high potential for employment in high-performance analogue signal processing [38].

2010, Abuelma’ati Presented a new oscillator circuits, showing that the Barkhausen criterion for the determination of the startup condition of oscillation and frequency of oscillation yields inaccurate results with relatively large errors depending on the selected component values and experimental work was carried out [39].

2. GENERAL DESCRIPTION OF OSCILLATORS AND ACTIVE BUILDING BLOCKS

In this chapter the basic knowledge about oscillators, current feedback operational amplifier and RC oscillator is presented.

2.1 Oscillators

Oscillators are special group of electrical circuits which does not process any signal, but on the contrary they are the source of electrical signals. They can be defined as autonomous circuits because they create the output signal without external excitation. Every electrical oscillator is characterized by amplitude and shape of the output voltage, frequency of oscillations and internal resistance, which is linear for a certain range of load resistance. From the point of power consumption, it can be considered as four port. Its entrance are the power supply pins and the output are the oscillation pins. From which is clear that the power efficiency of the oscillator can be defined as ratio between input dc and output ac power. One of the main parts of the oscillator circuit is the power amplifier block which is used to add energy to the oscillation in right time to secure oscillations continuance. With the first operational amplifier circuits being used for the oscillators construction, mostly classic voltage operational amplifier has been used for the purpose of power amplification and feedback, but with time different blocks have been created with different advantages and disadvantages.

For creation of the oscillation there are 3 major conditions which have to be accomplished.

Those are:

1. The amplitude condition: An oscillator will create stable oscillations only when product of the feedback block and the amplifier block will be equal to 1 => $\beta A = 1$. Usually this product is set a little above one, this provides certain creation of the oscillations.
2. The phase condition: An oscillator will create stable oscillations only when the sum of phase shift of the feedback block and the amplifier block will be an integer multiple of 2π. Which equals to $\varphi = k.360 (k = 0,1,2,..)$.
3. The start condition: An oscillator will create oscillations when the power consumed by circuit will be lower than the power supplied.

By the shape of the output signal we can divide oscillators into two groups:

1. Harmonic wave generators where the shape of the output signal is sine wave i.e., it can be interpreted by sine or cosine function.

2. Shape generators where the shape of the output signal can be triangular, rectangular, saw, or pulses. This signal cannot be interpreted by sine or cosine function but Fourier analysis can be used for its description.

For oscillation creation an energy addition is needed in right time so the oscillation condition can be hold. Because of this, circuit involves part which automatically controls the energy addition in right time and also the circuit have to be supplied with more energy than it consumes. So Oscillator circuits usually involve at least one or more parts which are used as energy storage. By this we can divide oscillator circuit into three parts. First is the oscillation part where energy accumulation parts are suited, then the amplifier part which provides the amplitude increase and also is used for the feedback, and second is the DC power supply part which provides the additional energy needed for oscillation maintain.

Typically, oscillators are realized as one of these options:

1. LC oscillators with resonance circuit
2. RC oscillators realized as combination of resistive and capacitive component goal of achieving correct phase characteristic of the circuit
3. Oscillators using vibrations of piezoelectric crystal

2.1.1 RC oscillators

RC oscillator is basic oscillator type which is easy to construct because it does not require coils for its operation and the resistors and capacitors are connected in such way, that the created circuit will fulfil the oscillation conditions. The basic element of an RC oscillator is usually a positive feedback power amplifier, or circuit which uses part with negative differential resistance e.g.

RC oscillators can be divided to these two types:

1. Bridge oscillators
2. Gradually pushed phase oscillators

Bridge oscillators:

Those oscillators use a band-pass principle around the critical frequency of f_0. It uses both positive and negative feedback. In comparison with gradually pushed phase oscillators the bridge oscillators have several benefits. It is a selective circuit, according to this the amplitude condition is fulfilled and circuit have only small shape distortion of the output signal. Also small phase changes will cause nearly unnoticeable frequency changes, which means very good frequency stability.

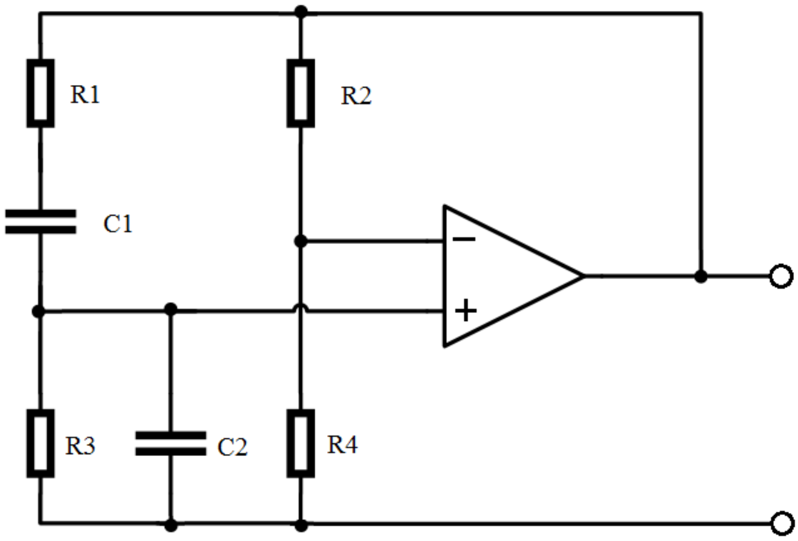

Figure 2.1 Bridge oscillator

Gradually phase pushed oscillators:

These oscillators are usually used in low frequency applications, they work with one feedback branch and consist of tree integrative or derivative elements connected in cascade inverting the phase for 180°. This in combination with inverted input fulfils the phase condition.

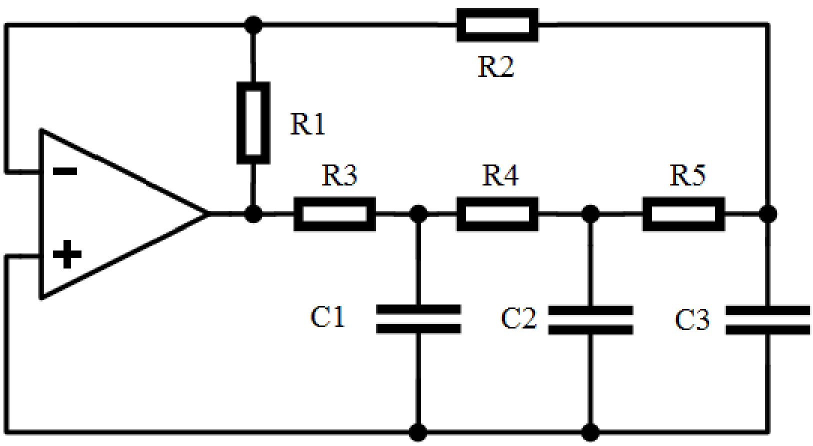

Figure 2.2 Phase pushed oscillator

2.2 Modern building blocks and Used Analog Building Blocks

Technological progress and development constantly leads to creation of better active building blocks and improvement of their parameters. One of the main factors of this improvement is usability of those blocks for higher frequencies and electrical alteration of some of the circuit parameters. Building blocks are generally constructed to work in three modes. If voltage is used as the information carrier, block is working in voltage mode, same rule applies for the current mode. If circuit uses both, voltage and current mode blocks, it is working in the third – mixed mode.

List of modern active building blocks:

OPA – Operation amplifier

CC – Current conveyor

CA – Current amplifier

CFOA – Current-feedback operational amplifier

OTA – Operational transconductance amplifier

VCA – Voltage controlled amplifier

CDTA – Current differencing transconductance amplifier

CDBA – Current differencing buffered amplifier

2.2.1 CFOA

The current feedback operational amplifier or transimpedance is popular device widely used in current mode circuits and their voltage mode counterparts. If the compensation terminal of CFOA is externally accessible, high versatility to design filters and oscillators is obtained. CFOA is an active circuit element which is usually composed of second generation current conveyor (CCII+) and a voltage follower (buffer). Input of this type of amplifier is sensitive to current rather that voltage as it is in the conventional voltage-feedback operational amplifier or VFOA. Thanks to the fact that CFOA transistors work in current mode, and because of the circuit formation, flexible gain and bandwidth is achievable over a wide range relatively independent of closed-loop gain. It also provides high slew-rate and operational frequency range and it is easy to realize various functions with the least possible number of external passive components, usually without any component-matching requirements. For actual CFOA the values of the external components must be carefully chosen to avoid the need to consider the parasitic impedances which are associated with the CFOA terminals, especially when operating at very high frequency

The current feedback operational amplifier is a four port with following characteristics:

*High slew-rate

*Flexible gain bandwidth achievable over a wide range of closed-loop gain

*High operational frequency range

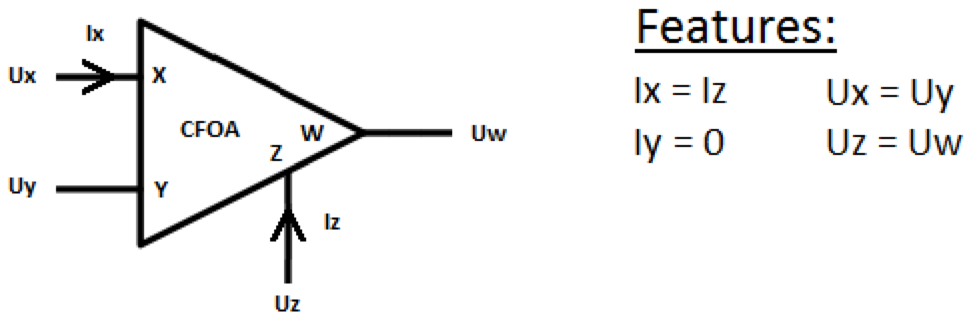

Figure 2.3 CFOA symbol diagram

Mathematical definition:

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \\ V_O \end{bmatrix} = \begin{bmatrix} 0\ 0\ 0\ 0 \\ 1\ 0\ 0\ 0 \\ 0\ 1\ 0\ 0 \\ 0\ 0\ 1\ 0 \end{bmatrix} \cdot \begin{bmatrix} V_Y \\ I_X \\ V_Z \\ I_O \end{bmatrix}$$

Where V_X, V_Y, V_Z, V_O, I_X, I_Y, I_Z and I_O are the voltages and the currents of X-, Y-, Z- and O-terminals respectively. The symbol diagram of CFOA is shown in Fig2.3.

2.2.2 MCDBA

Modified Current Differencing Buffered Amplifier (MCDBA)

A current differencing buffed amplifier (CDBA) is a multi-terminal active component with two inputs and two outputs. This circuit is derived from CFA and was developed by Cevdet Acar and Serdar Ozoguz. The CDBA is able to operate in high frequency range of hundreds of MHz or even GHz and is suitable for current operation mode while it still provides a voltage output.

In 1998, Acar and Ozoguz presented literature about the voltage-monitoring current-difference amplifier (CDBA) active component. Several analog circuit applications have been realized using this active element and various advantages of this active element have been demonstrated. In this thesis, the CDBA element was changed to introduce an oscillator circuit that can be implemented using a minimum number of active and passive elements. The non-ideal definition indices of the modified CDBA element are given in Eq. (4.1) and in Figure 4.1.

$$\begin{bmatrix} v_p \\ v_n \\ i_{z1} \\ i_{z2} \\ v_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ k & -k & 0 & 0 & 0 \\ -k & k & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_p \\ i_n \\ v_{z1} \\ v_{z2} \\ i_w \end{bmatrix} \tag{4.1}$$

Here, the gain of the (i_p - i_n) current is adjusted by the k parameter and the value of k is controlled by the current I_a.

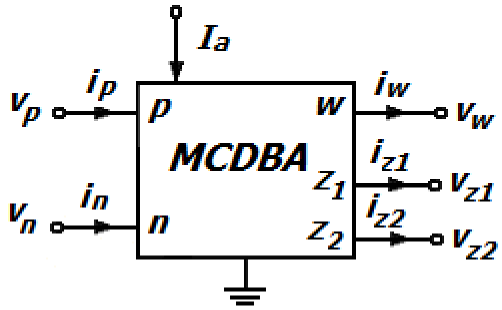

Figure 2.3 MCDBA symbol diagram

3. ACTIVE RC SINUSOIDAL OSCILLATOR CIRCUIT

3.1 Analysis

3.1.1 CFOA oscillator

Oscillator circuit presented in 2010 by Abuelma'ati has been chosen as the first simulated circuit. This circuit uses two current feedback operational amplifiers [39].

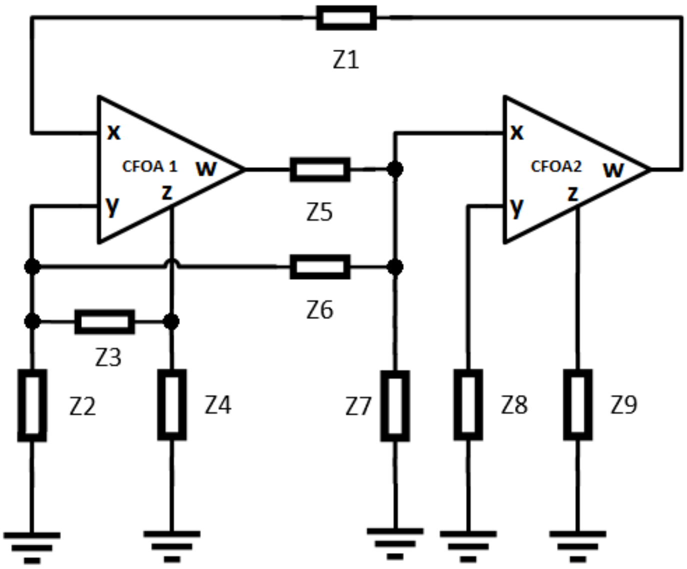

Figure 3.1.1 General active RC sinusoidal circuit

Different oscillators can be designed with the circuit shown in Figure 3.1. By considering $Y2 = Y3 = Y7 = 0$, $Y5 = Y6 = \infty$, the following circuit is received:

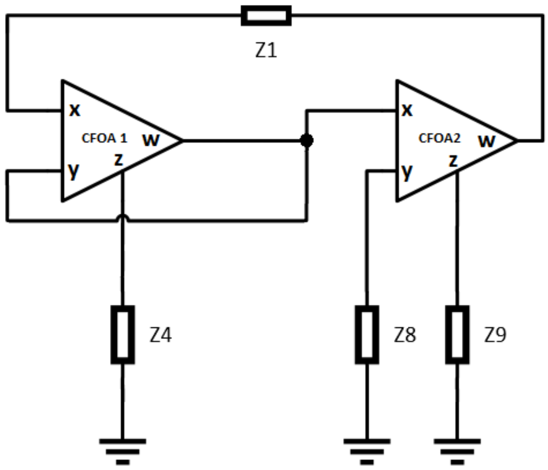

Figure 3.1.2 Active RC sinusoidal circuit by considering $Y2 = Y3 = Y7 = 0$, $Y5 = Y6 = \infty$.

By changing the impedance values, total number of eighteen different circuits can be achieved. Those impedance values are given by following table.

Table 3.1.1 Impedance values for $Y2 = Y3 = Y7 = 0$, $Y5 = Y6 = \infty$

	$\boldsymbol{Z4}(\boldsymbol{Y4})$	$\boldsymbol{Z9}(\boldsymbol{Y9})$	$\boldsymbol{Z8}(\boldsymbol{Y8})$	$\boldsymbol{Z1}(\boldsymbol{Y1})$
A	$1/R4+sC4$	$1/R9+sC9$	$R8$	$R1$
B	$R4$	$R9$	$1/R8+sC8$	$1/R1+sC1$

C	$R4$	$1/R9+sC9$	$R8$	$1/R1+sC1$
D	$1/sC4+R4$	$1/sC9+R9$	$R8$	$R1$
E	$1/sC4+R4$	$R9$	$1/sC8+R8$	$R1$
F	$R4$	$R9$	$1/sC8+R8$	$1/sC1+R1$
G	$1/sC4+R4$	$1/R9+sC9$	$R8$	$R1$
H	$1/sC4+R4$	$R9$	$1/R8+sC8$	$R1$
I	$R4$	$1/sC9+R9$	$1/R8+sC8$	$R1$
J	$R4$	$1/sC9+R9$	$R8$	$1/R1+sC1$
K	$R4$	$R9$	$1/sC8+R8$	$1/R1+sC1$
L	$1/R4+sC4$	$1/sC9+R9$	$R8$	$R1$
M	$1/R4+sC4$	$R9$	$1/sC8+R8$	$R1$
N	$1/R4+sC4$	$R9$	$R8$	$1/sC1+R1$
O	$R4$	$1/R9+sC9$	$1/sC8+R8$	$R1$
P	$R4$	$1/R9+sC9$	$R8$	$1/sC1+R1$
R	$R4$	$R9$	$1/R8+sC8$	$1/sC1+R1$
S	$1/sC4+R4$	$R9$	$R8$	$1/R1+sC1$

Next, circuit realized by using values given in Table XX A is examined. The final form of the circuit is showed in Figure XX.

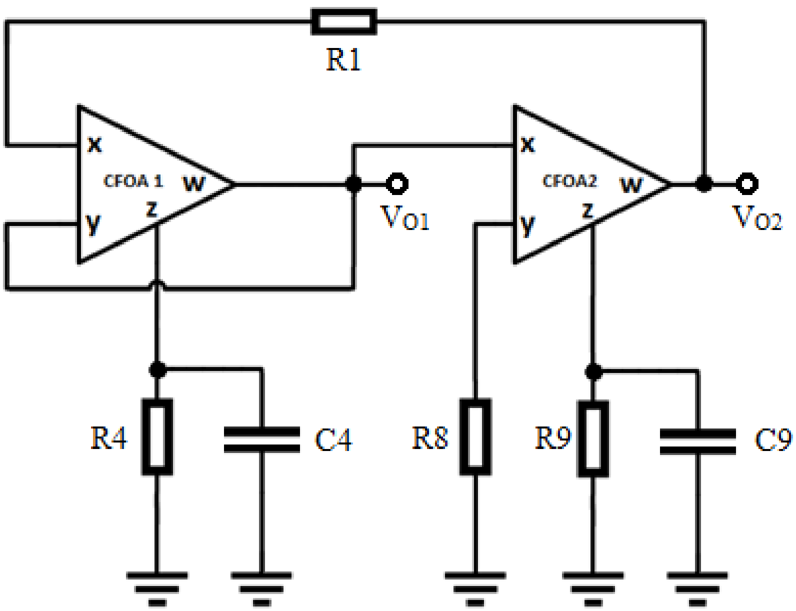

Figure 3.1.3 Active RC sinusoidal oscillator circuit

3.1.2 MCDBA oscillator

In this section a quadrature oscillator circuit is presented, using the MCDBA as active element. Since the current outputs are high resistance and the voltage outputs are low resistance, another circuit can be easily connected without buffer circuit, also the proposed circuit structure can operate in voltage and current mode. There are two MCDBAs, two capacities and two resistance elements in the circuit. One end of all passive elements is connected to the voltage-clamped 0 V terminal of the MCDBA element. The theoretical analysis of the dynamics was carried out and simulations were carried out with the PSPICE program to show the accuracy of the analyses. The orthogonal oscillator circuits form 90o phase different output signals and are used especially in communication circuits. The orthogonal oscillator circuit proposed in this thesis is obtained by connecting two all-pass filter circuits 180o phase-by-phase with each other and connecting the output of the second all-pass filter to the input of the first all-pass filter. In the literature there is a current-mode all-pass filter structure using a minimum number of passive elements and one CDBA active element. These circuit configurations are given in Figure

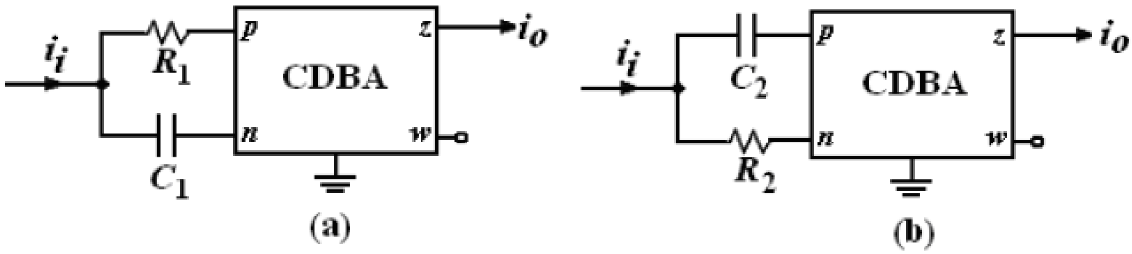

Figure 3.1.4 CDBA based current mode all pass filter circuits

The diagonal oscillator circuit can not be obtained by connecting all the passive filters given in Figure 3.1.4. When the non-ideal effects of CDBA are considered, it has been seen that the z output current must be multiplied by a certain k coefficient. The MCDBA element was obtained by changing the definition associations of the CDBA element. The orthogonal oscillator circuit implemented is shown in Figure 3.1.5.

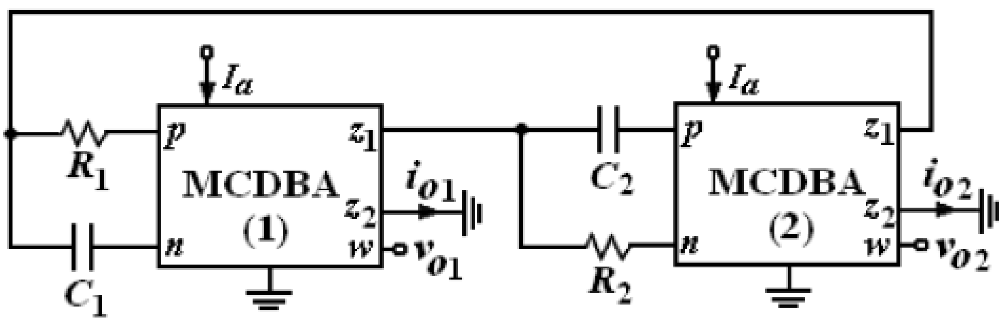

Figure 3.1.5 Orthogonal oscillator circuit using MCDBA.

Experimental study of the proposed orthogonal oscillator circuit was carried out in this thesis. For this, it is necessary for the MCDBA circuit to be realized by using commercially active elements. The CDBA element was demonstrated in a study by Acar and Özoğuz in 1999 using a commercially available Current Feedback Operational Amplifier (CFOA). In this study, the AD844 produced by Analog Device was used as CFOA element.

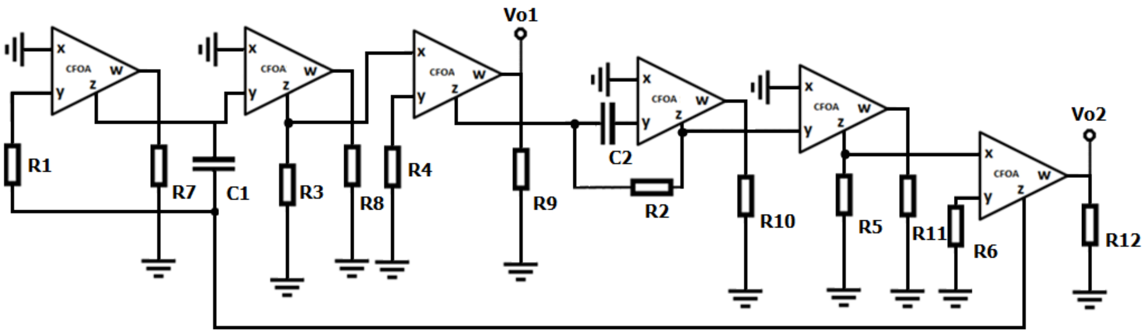

Figure 3.1.6 MCDBA oscillator circuit

3.2 Circuit analysis

3.2.1 CFOA

The mathematical analysis of the circuit in Figure 3.3.

$$i_{x1} = \frac{V_9 - V_4}{R_1} = i_{z1} \quad (3.1)$$

$$i_{z1} + i_{R4} + i_4 = 0 \quad (3.2)$$

$$i_4 = -V_4 R_4 - V_9 - V_4 R_1 \quad (3.3)$$

$$C_4 \frac{dV_4}{dt} = \frac{V_4}{R_1} - \frac{V_4}{R_4} - \frac{V_9}{R_1} \quad (3.4)$$

$$\frac{dV_4}{dt} = V_4 \left(\frac{R_4 - R_1}{R_1 R_4 C_4}\right) - V_9 \frac{1}{R_1 C_4} \quad (3.5)$$

$$i_{R8} = \frac{V_4}{R_8} \quad (3.6)$$

$$i_{x2} = -\frac{V_4}{R_8} = i_{z2} \quad (3.7)$$

$$i_{z2} + i_{R9} + i_9 = 0 \quad (3.8)$$

$$C_9 \frac{dV_9}{dt} = \frac{V_4}{R_8} - \frac{V_9}{R_9} \tag{3.9}$$

$$\frac{dV_9}{dt} = V_4 \frac{1}{R_8 C_9} - V_9 \frac{1}{R_9 C_9} \tag{3.10}$$

With use of differential equations obtained in Eq. (3.5) and Eq. (3.10), the following equations are found.

$$\frac{d}{dt}\begin{bmatrix} V_4 \\ V_9 \end{bmatrix} = \begin{bmatrix} \frac{R_4 - R_1}{R_1 R_4 C_4} & -\frac{1}{R_1 C_4} \\ \frac{1}{R_8 C_9} & -\frac{1}{R_9 C_9} \end{bmatrix} \begin{bmatrix} V_4 \\ V_9 \end{bmatrix} \tag{3.11}$$

$$\begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} - \begin{bmatrix} \frac{R_4 - R_1}{R_1 R_4 C_4} & -\frac{1}{R_1 C_4} \\ \frac{1}{R_8 C_9} & -\frac{1}{R_9 C_9} \end{bmatrix} = \begin{bmatrix} s - \frac{R_4 - R_1}{R_1 R_4 C_4} & \frac{1}{R_1 C_4} \\ -\frac{1}{R_8 C_9} & s + \frac{1}{R_9 C_9} \end{bmatrix} \tag{3.12}$$

$$\left(s - \frac{R_4 - R_1}{R_1 R_4 C_4}\right)\left(s + \frac{1}{R_9 C_9}\right) - \left(-\frac{1}{R_8 C_9}\right)\left(\frac{1}{R_1 C_4}\right) = 0 \tag{3.13}$$

$$s^2 + s\frac{1}{R_9 C_9} - s\frac{R_4 - R_1}{R_1 R_4 C_4} - \frac{R_4 - R_1}{R_1 R_4 R_9 C_4 C_9} + \frac{1}{R_1 R_8 C_4 C_9} \tag{3.14}$$

$$s^2 + s\left(\frac{R_1 R_4 C_4 - R_4 R_9 C_9 + R_1 R_9 C_9}{R_1 R_4 R_9 C_4 C_9}\right) + \left(\frac{R_1 R_8 + R_4 R_9 - R_4 R_8}{R_1 R_4 R_8 R_9 C_4 C_9}\right) = 0 \tag{3.15}$$

The equation (3.15) shows the characteristic equation of the oscillator. Equations for oscillation frequency and condition follows.

$$R_1 R_4 C_4 - R_4 R_9 C_9 + R_1 R_9 C_9 = 0 \qquad \text{(Barkhausen criterion)} \tag{3.16}$$

$$\omega_0 = \sqrt{\frac{R_1 R_8 + R_4 R_9 - R_4 R_8}{R_1 R_4 R_8 R_9 C_4 C_9}} \tag{3.17}$$

If $R_4 = R_8 = R_9$ and $C_4 = C_9 = C$, then the oscillation frequency and condition are as follows.

$$R_1 = \frac{R}{2} \tag{3.18}$$

$$\omega_0 = \frac{1}{RC} \tag{3.19}$$

3.2.2 MCDBA

An all-pass filter circuit is achieved by adding a resistor and a capacitor in parallel to the p and n pins of the MCDBA. Transfer function of this circuit is follows.

$$H(s) = \frac{I_0(s)}{I_i(s)} = -\frac{s-\frac{1}{R_1C_1}}{s+\frac{1}{R_1C_1}} \tag{3.20}$$

Two of those filters are used as the basis of the oscillator, the amount of phase shift provided by the first and second all-pass filter circuit follows.

$$\varphi(\omega) = -2\arctan(\omega R_1 C_1) \tag{3.21}$$

$$\varphi_2(\omega) = 180 - 2\arctan(\omega R_2 C_2) \tag{3.22}$$

When the non-ideal effects of CDBA are considered, it has been seen that the z output current must be multiplied by a certain k coefficient. The characteristic equation obtained by using the ideal definition relations of the MCDBA active element follows.

$$s^2 - s\frac{(k_1k_2-1)(C_1R_1+C_2R_2)}{C_1C_2R_1R_2(1+k_1k_2)} + \frac{1}{C_1C_2R_1R_2} = 0 \tag{3.23}$$

Then the oscillation condition and the oscillation frequency of the oscillator are as follows.

$$k_1k_2 - 1 = 0 \tag{3.24}$$

$$\omega_o = \frac{1}{\sqrt{C_1C_2R_1R_2}} \tag{3.25}$$

3.3 Simulation Results

CFOA

The PSpice schematic prepared for the circuit simulation is given in Figure 3.4.

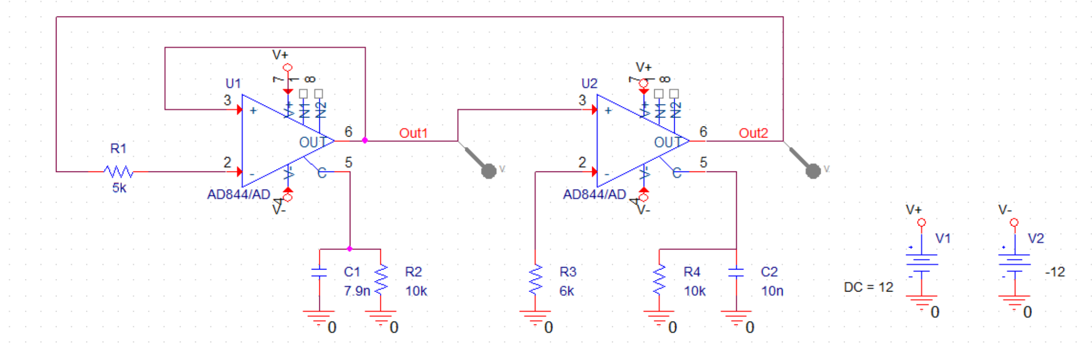

Figure.3.4 PSpice circuit schematic

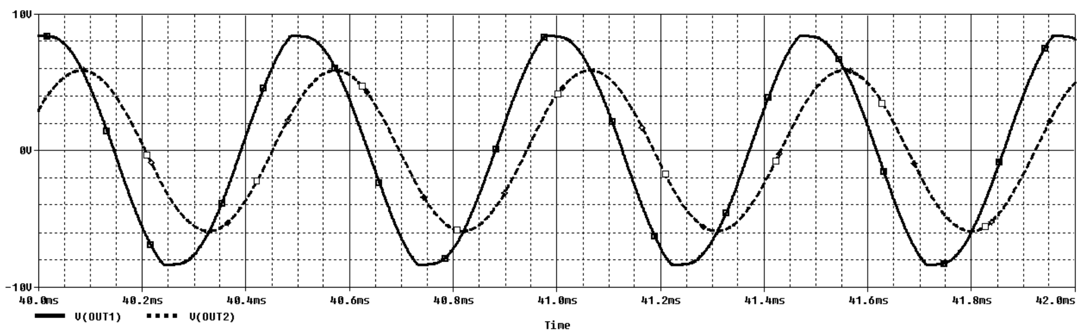

Figure 3.5 Output voltages with the parameters R_1 = 4.8kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 7.9nF in PSpice.

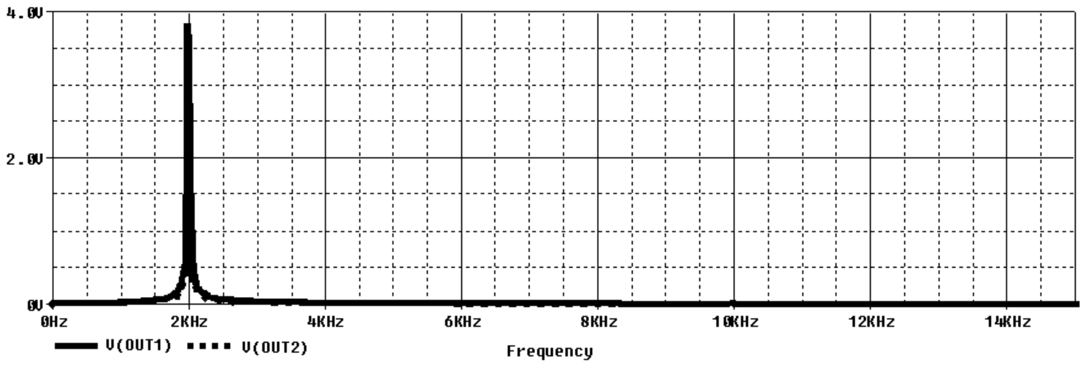

Figure 3.6 Frequency spectrum with the parameters R_1 = 4.8kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 7.9nF in PSpice.

Square wave is observed at output V_{out1} when R_1 = 50 Ω, the results are displayed below.

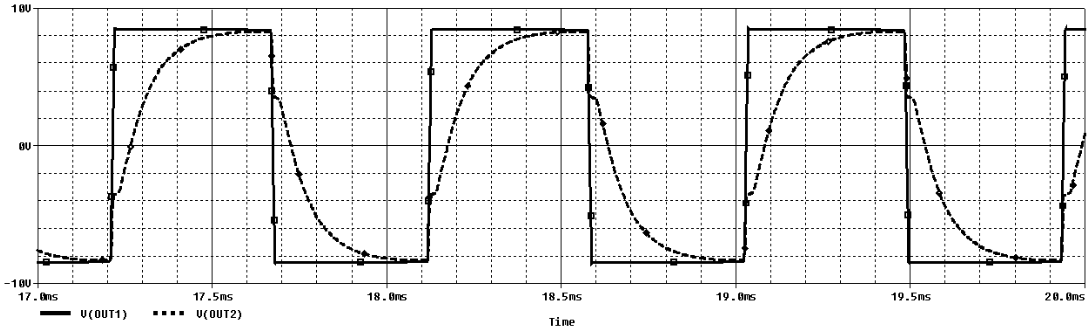

Figure 3.7. Output voltages with the parameters R_1 = 50Ω, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 7.9nF in PSpice.

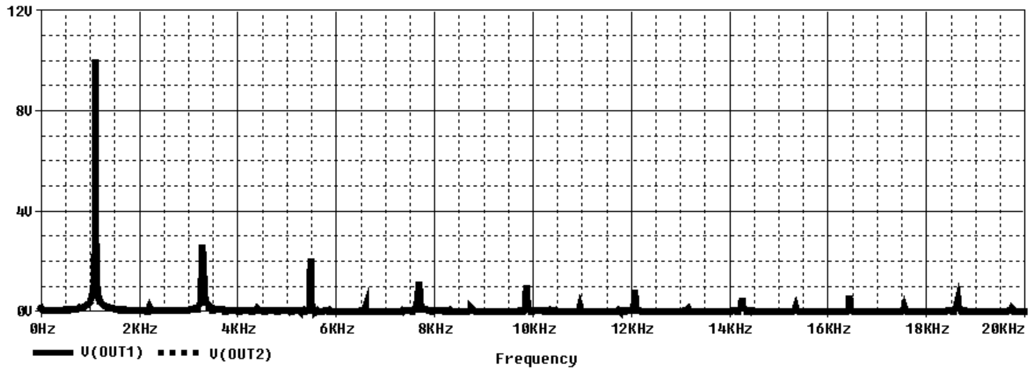

Figure 3.8. Frequency spectrum with the parameters R_1 = 50Ω, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 7.9nF in PSpice.

The circuit is able to operate over a wide frequency range. When C_4 = C_9 = 22uF, the frequency falls below 1Hz. The results are below.

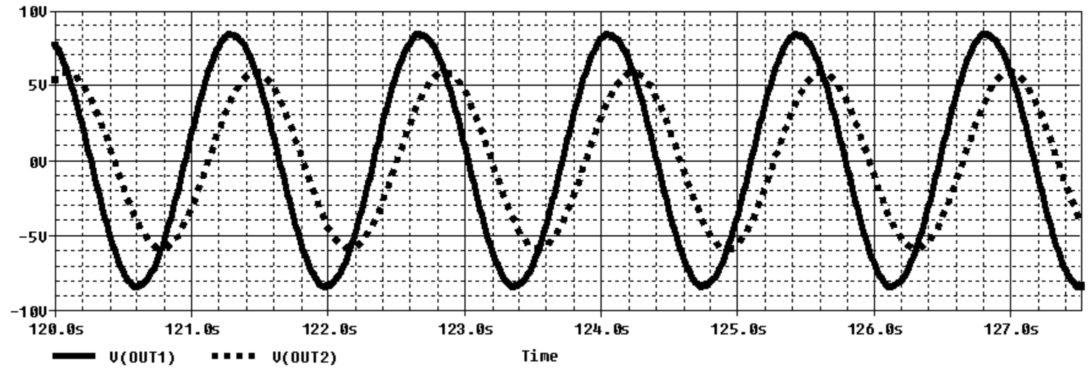

Figure 3.9. Output voltages with the parameters R_1 = 4.8kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 22uF in PSpice.

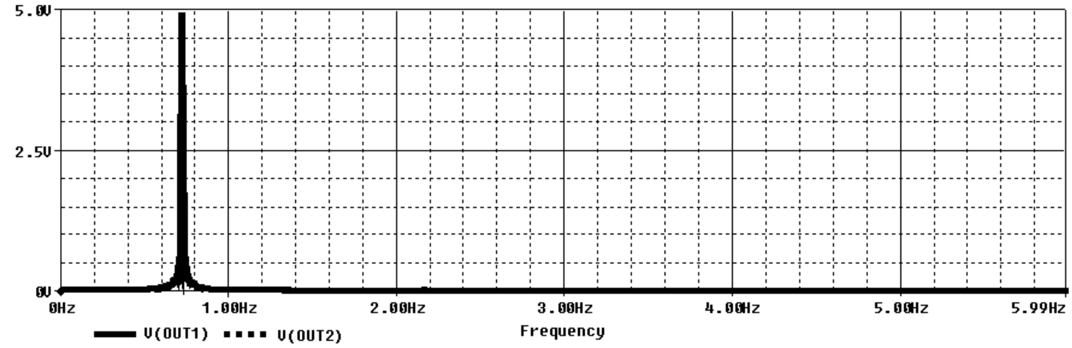

Figure 3.10. Frequency spectrum with the parameters R_1 = 4.8kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 22uF in PSpice.

The circuit can also operate at high frequencies. When R_1 = 230Ω, R_4 = $R8$ = R_9 = 500Ω and C_4 = C_9 = 10pF, the frequency is 9.2MHz, the results are below.

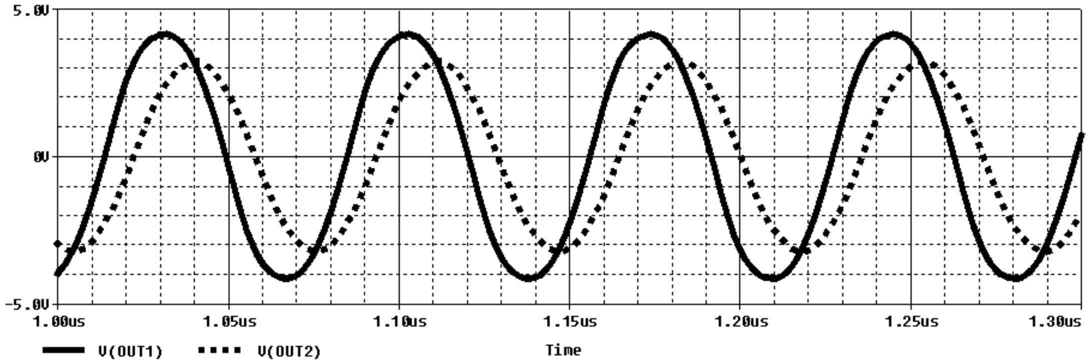

Figure 3.11. Output voltages with the parameters R_1 = 230Ω, R_4 = R_8 = R_9 = 500Ω and $C4$ = $C9$ = 10pF in PSpice.

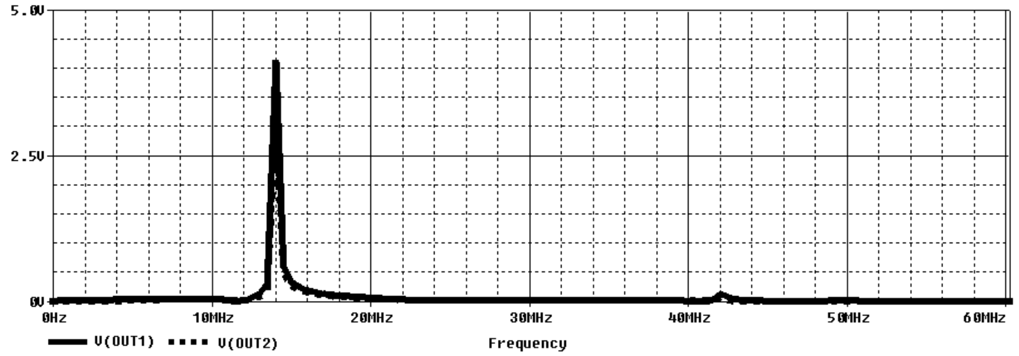

Figure 3.12. Frequency spectrum with the parameters R_1 = 230Ω, R_4 = R_8 = R_9 = 500Ω and $C4$ = $C9$ = 10nF in PSpice.

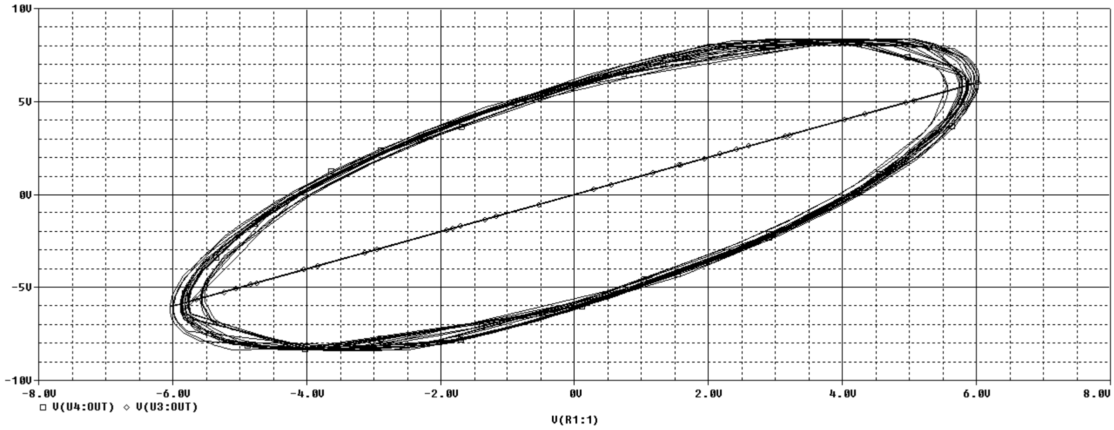

Figure 3.13 Shows the lissajous curve for R_1 = 4.8kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 7.9nF in PSpice, phase difference of nearly $\pi/4$ can be seen between the output signals.

MCDBA

The PSpice schematic prepared for the circuit simulation is given in Figure 3.13.

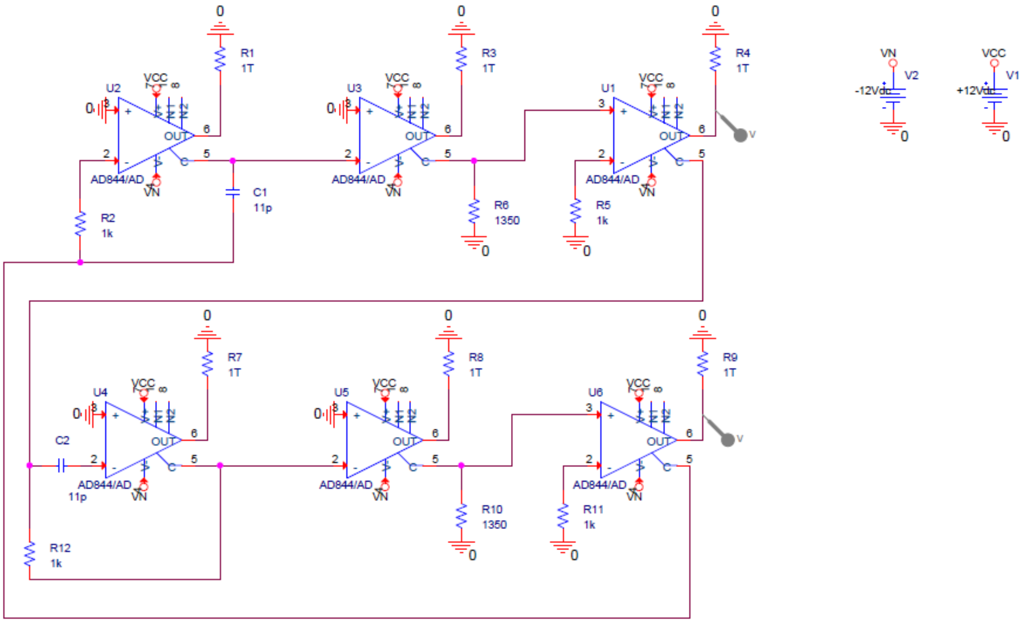

Figure.3.14 PSpice circuit schematic.

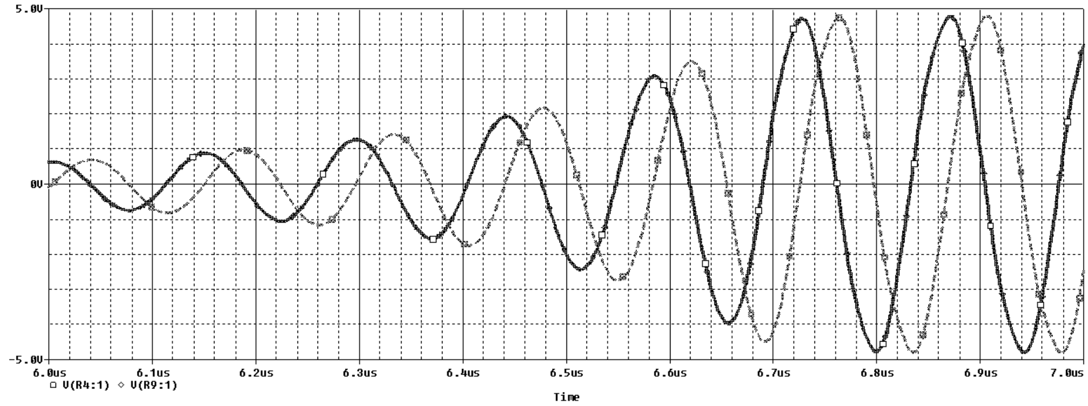

Figure 3.15 Output voltages with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 12pF in PSpice.

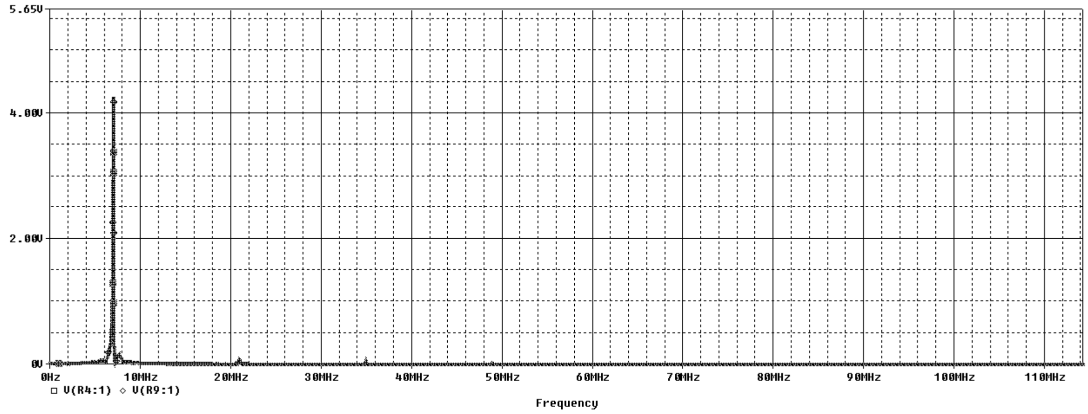

Figure 3.16 Frequency spectrum with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 12pF in PSpice.

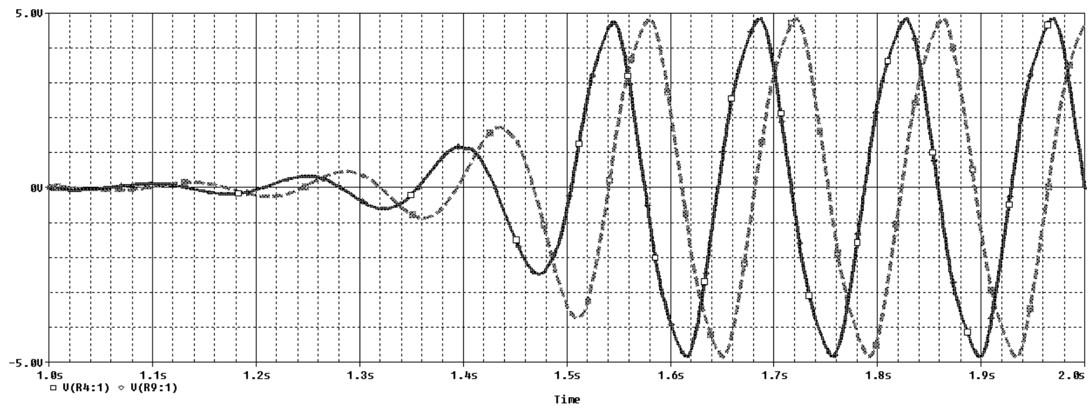

Figure 3.17 Output voltages with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 22uF in PSpice.

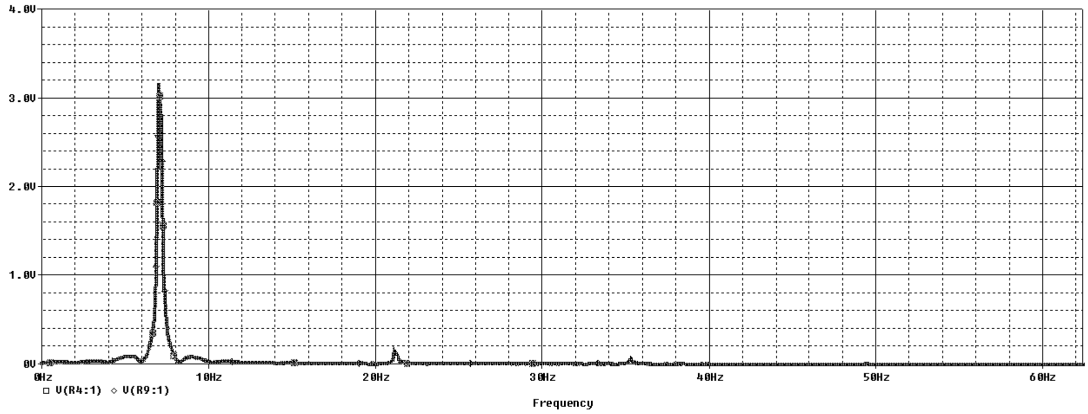

Figure 3.18 Frequency spectrum with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 22uF in PSpice.

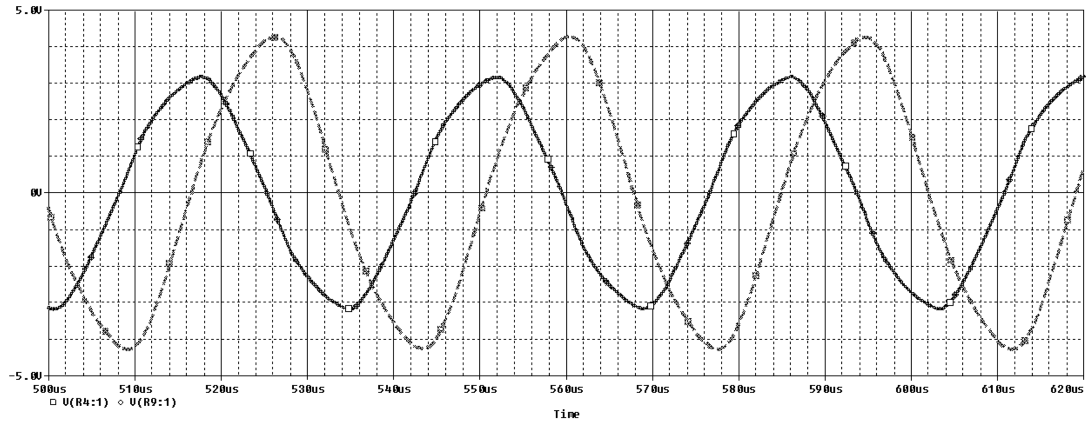

Figure 3.19 Output voltages with the parameters R_1 = 0.6kΩ, R_2 = 1kΩ and $C1$ = $C2$ = 6.8nF in PSpice.

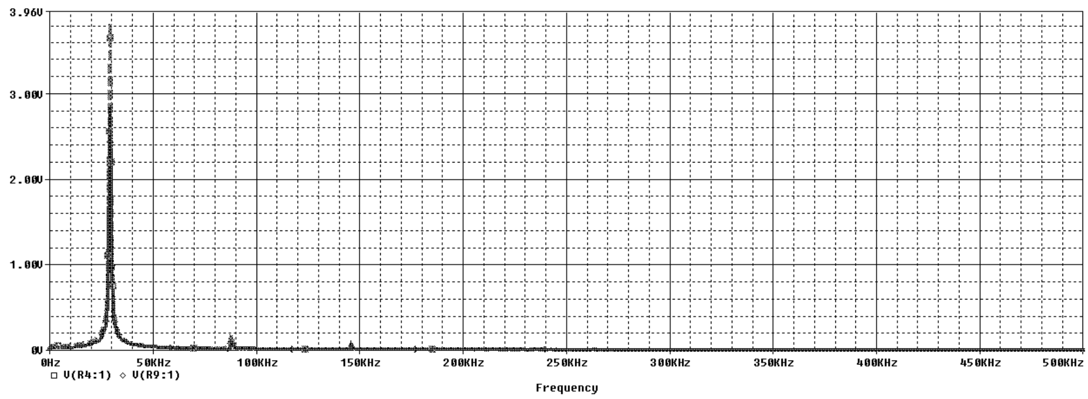

Figure 3.20 Frequency spectrum with the parameters R_1 = 0.6kΩ, R_2 = 1kΩ and $C1$ = $C2$ = 6.8nF in PSpice.

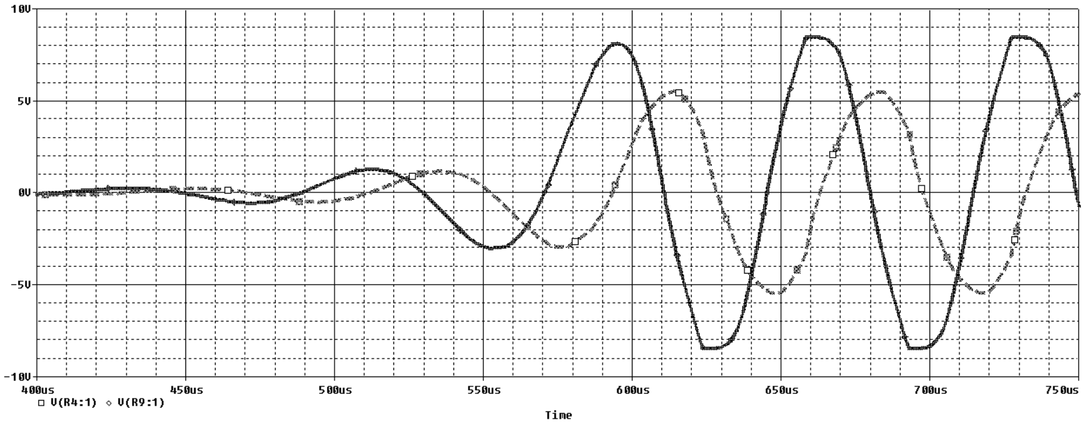

Figure 3.21 Output voltages with the parameters R_1 = 3.2kΩ, R_2 = 1kΩ and $C1$ = $C2$ = 6.8nF in PSpice.

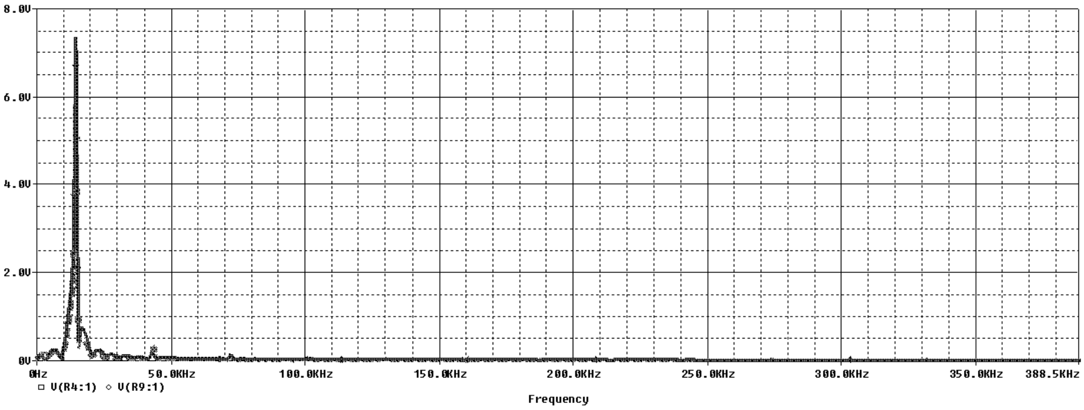

Figure 3.22 Frequency spectrum with the parameters R_1 = 3.2kΩ, R_2 = 1kΩ and $C1$ = $C2$ = 6.8nF in PSpice.

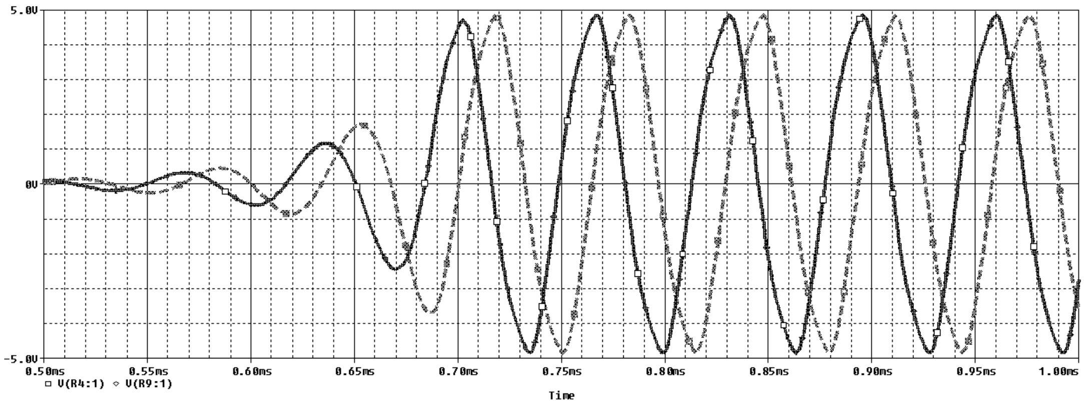

Figure 3.23 Output voltages with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 10nF in PSpice.

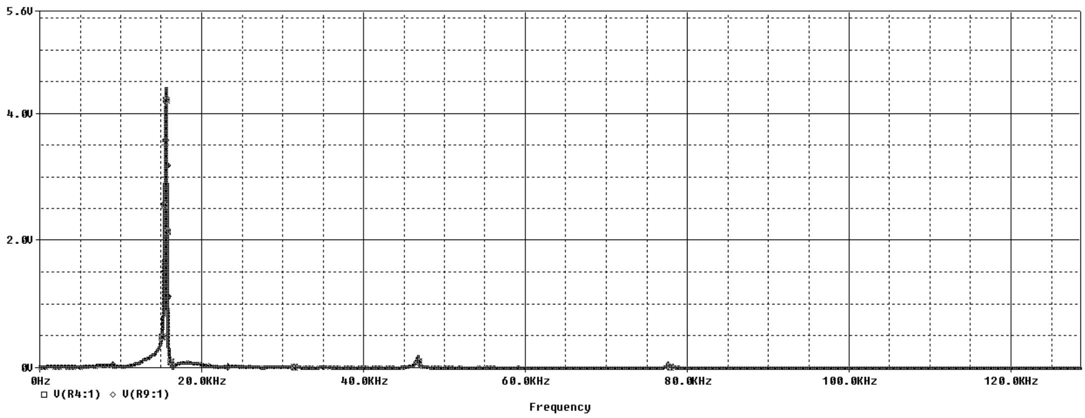

Figure 3.24 Frequency spectrum with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 10nF in PSpice.

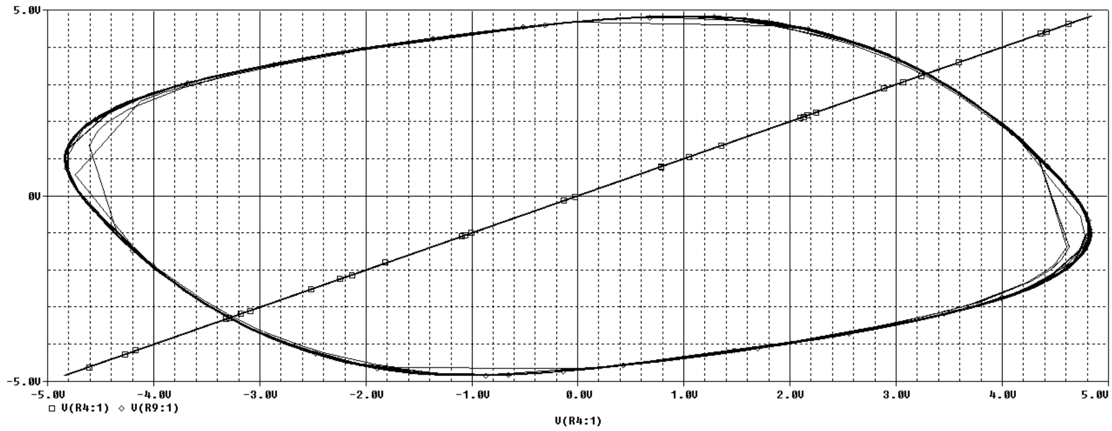

Figure 3.25 Shows the lissajous curve for R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 22uF in PSpice, phase difference of nearly $\pi/4$ can be seen between the output signals.

4. MEASUREMENT RESULTS

4.1 Breadboard measurement

CFOA

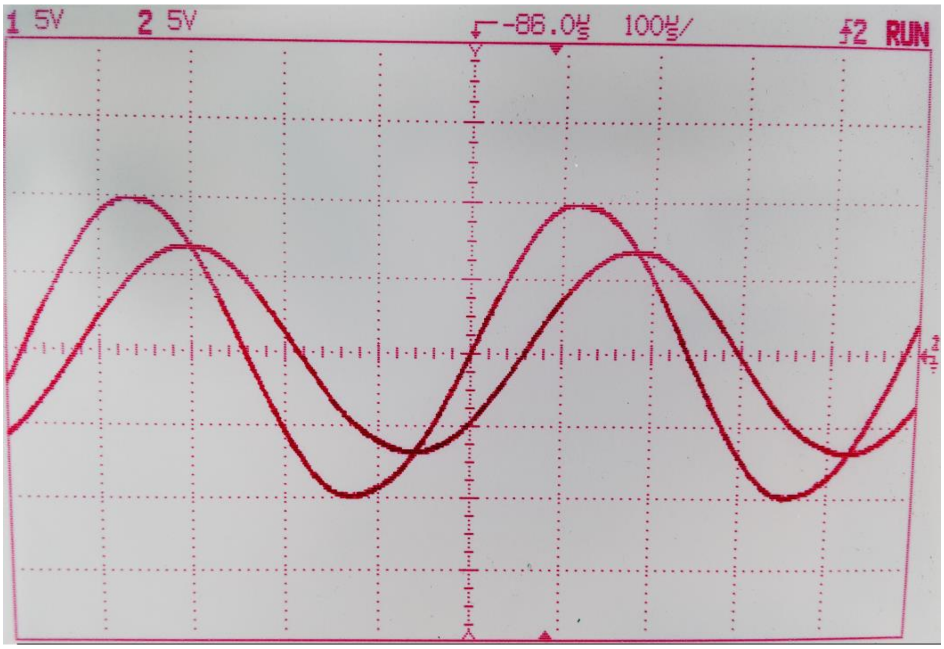

Figure 4.1 Output voltages with the parameters R_1 = 4.7kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 6.8nF measured on breadboard.

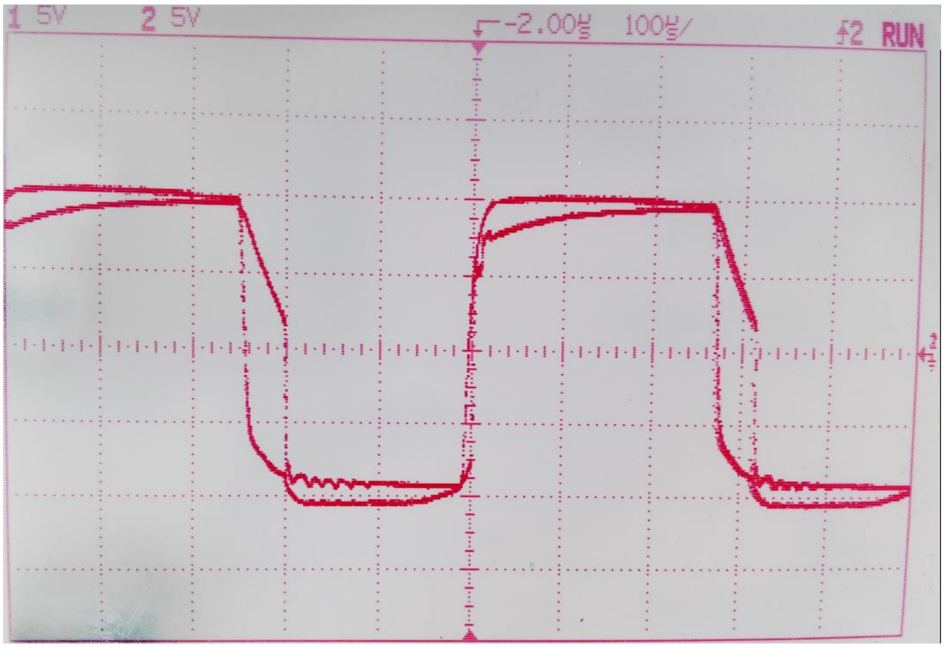

Figure 4.2 Output voltages with the parameters R_1 = 50Ω, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 6.8nF measured on breadboard.

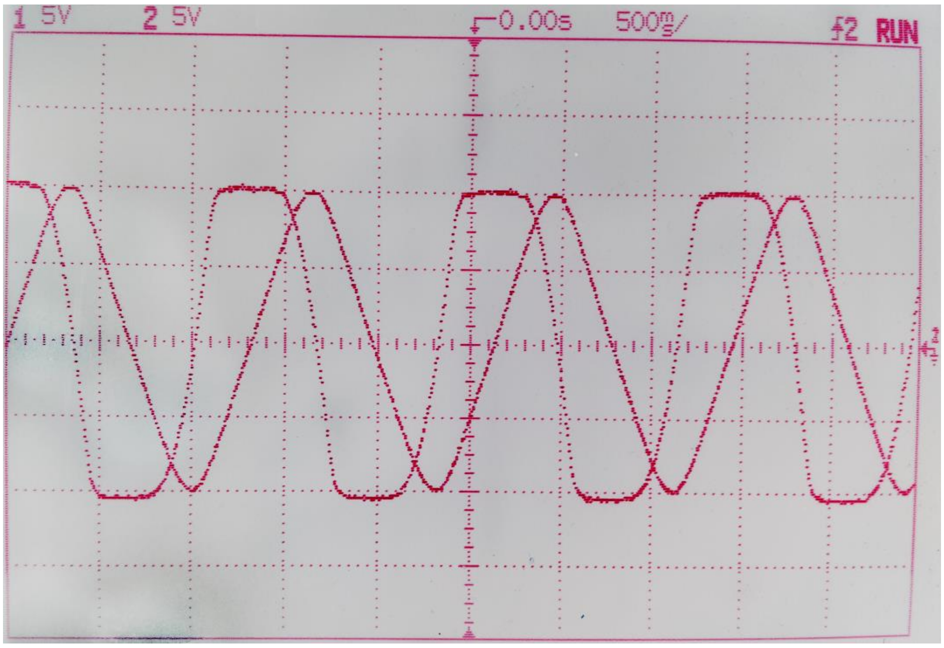

Figure 4.3 Output voltages with the parameters R_1 = 4.7kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 22uF measured on breadboard.

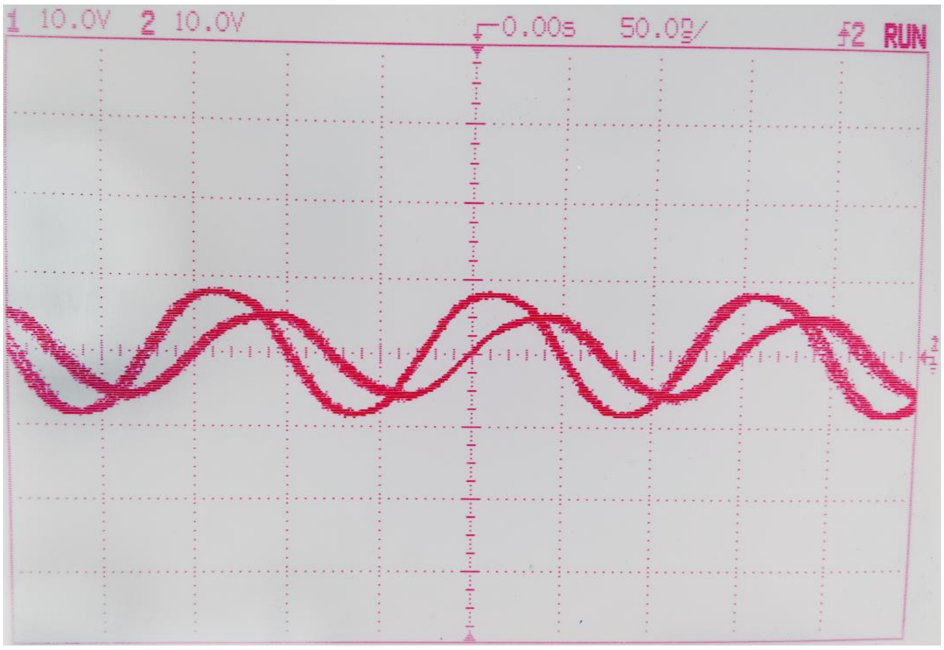

Figure 4.4 Output voltages with the parameters R_1 = 220Ω, R_4 = R_8 = R_9 = 560Ω and $C4$ = $C9$ = 10pF measured on breadboard.

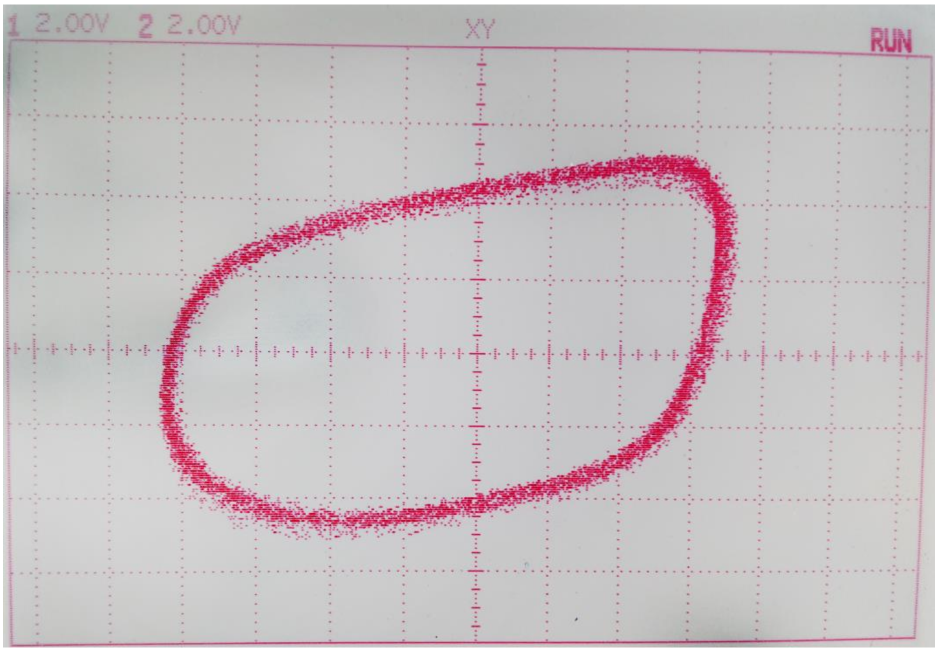

Figure 4.5 Shows the lissajous curve for the breadboard measurement.

MCDBA

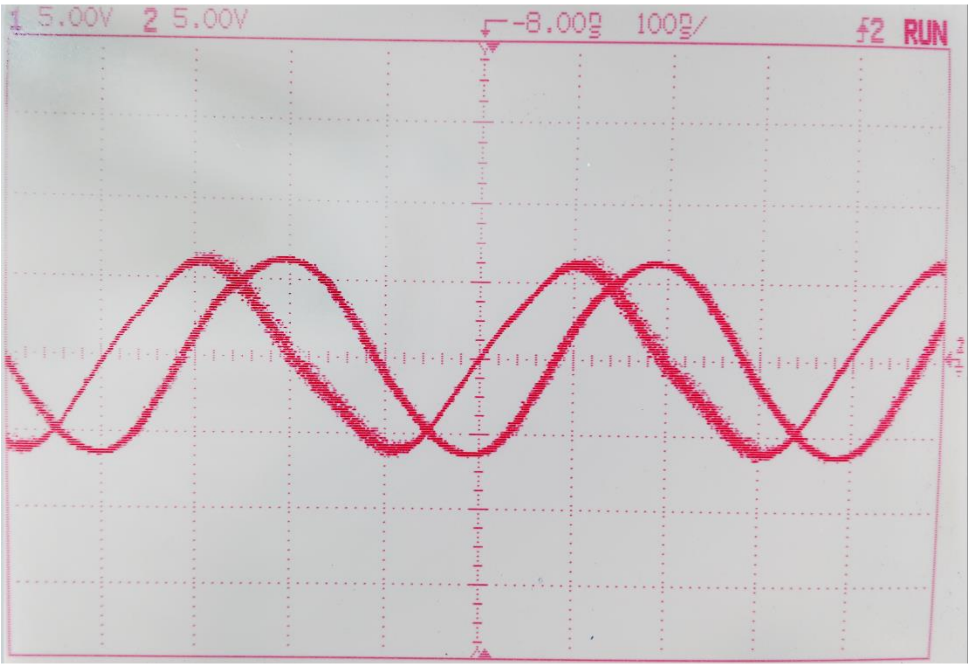

Figure 4.6 Output voltages with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 12pF measured on breadboard.

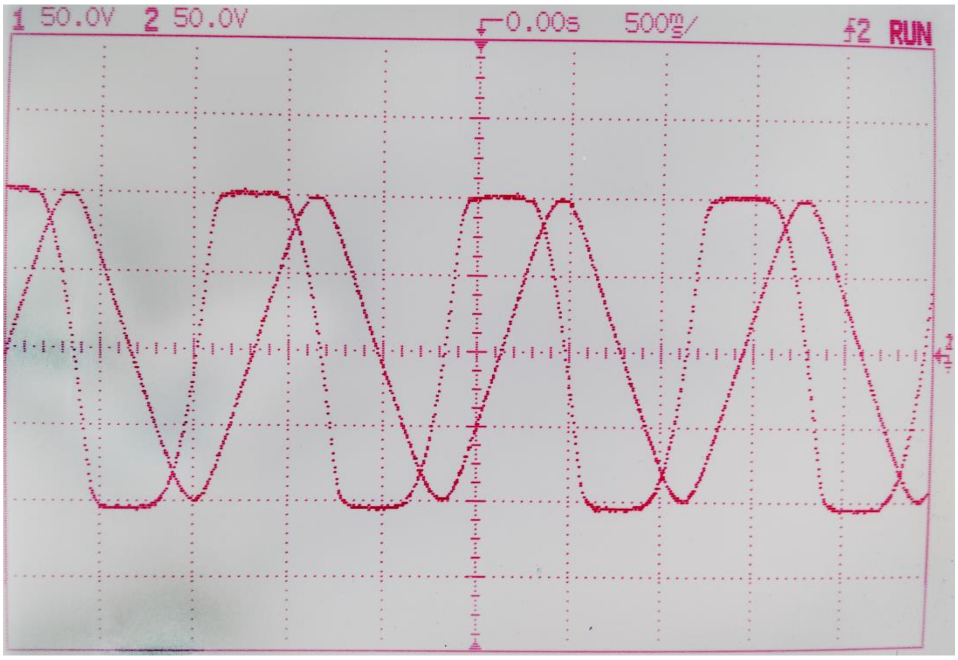

Figure 4.7 Output voltages with the parameters R_1 = R_2 = 1kΩ and $C1$ = $C2$ = 22uF measured on breadboard.

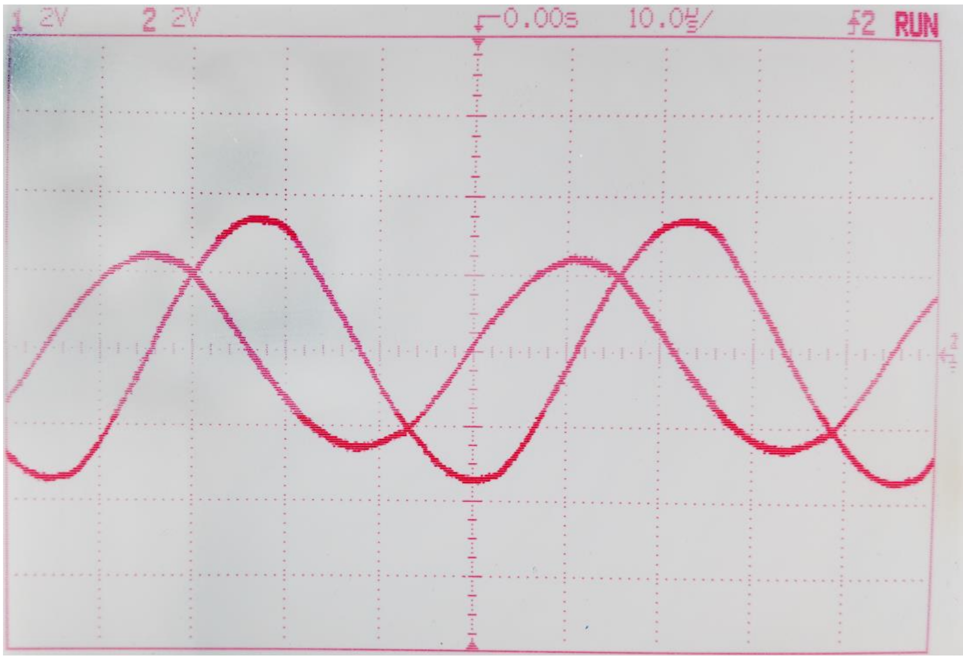

Figure 4.8 Output voltages with the parameters R_1 = 0.6kΩ, R_2 = 1kΩ and $C1$ = $C2$ = 6.8nF measured on breadboard.

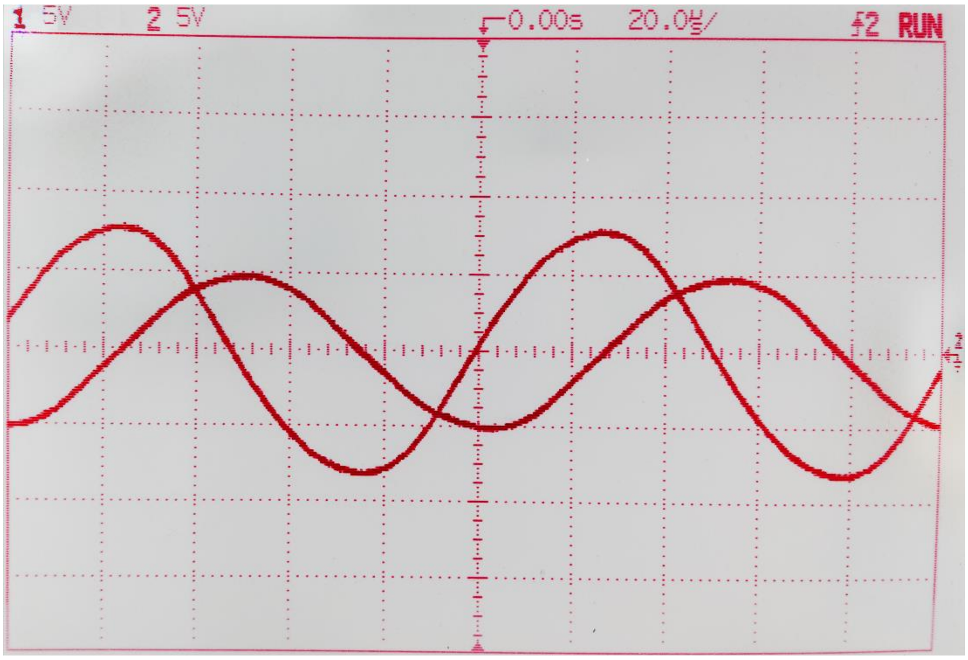

Figure 4.9 Output voltages with the parameters R_1 = 3.2kΩ, R_2 = 1kΩ and $C1 = C2$ = 6.8nF measured on breadboard.

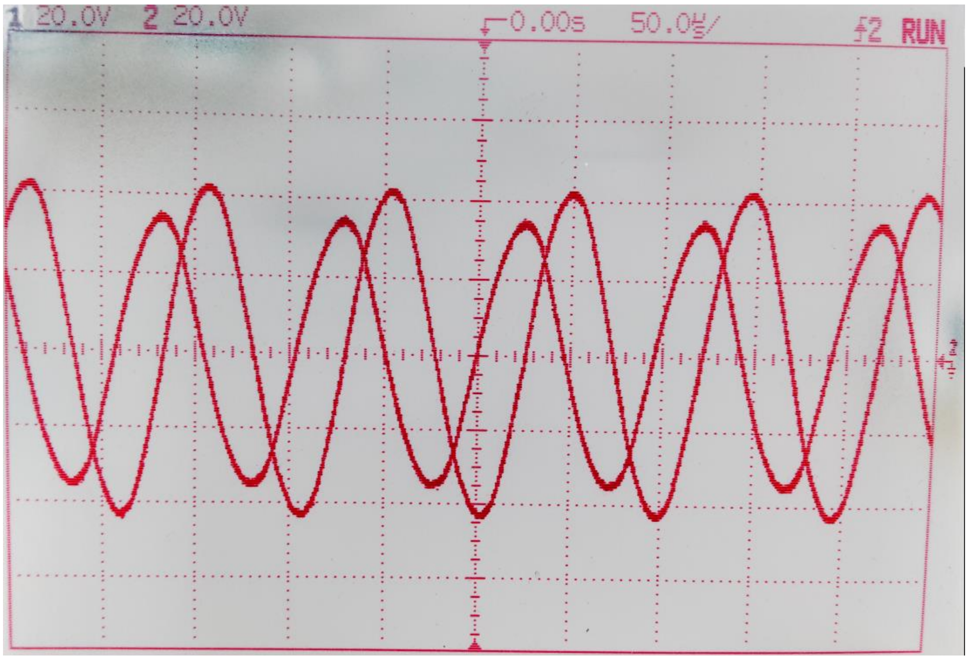

Figure 4.10 Output voltages with the parameters $R_1 = R_2$ = 1kΩ and $C1 = C2$ = 10nF measured on breadboard.

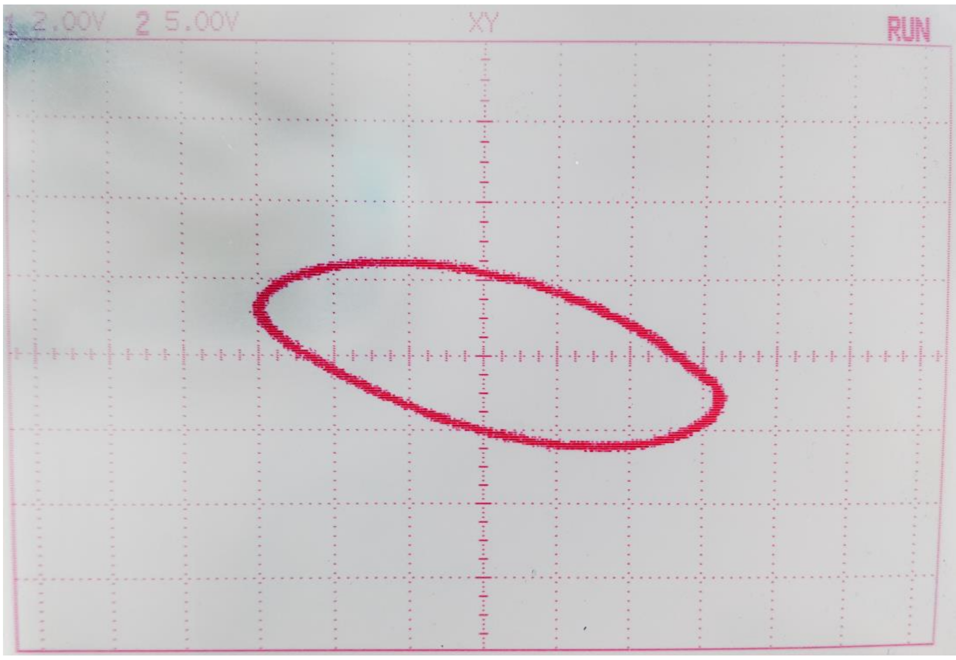

Figure 4.11 Shows the lissajous curve for the breadboard measurement.

4.2 PCB measurement

CFOA

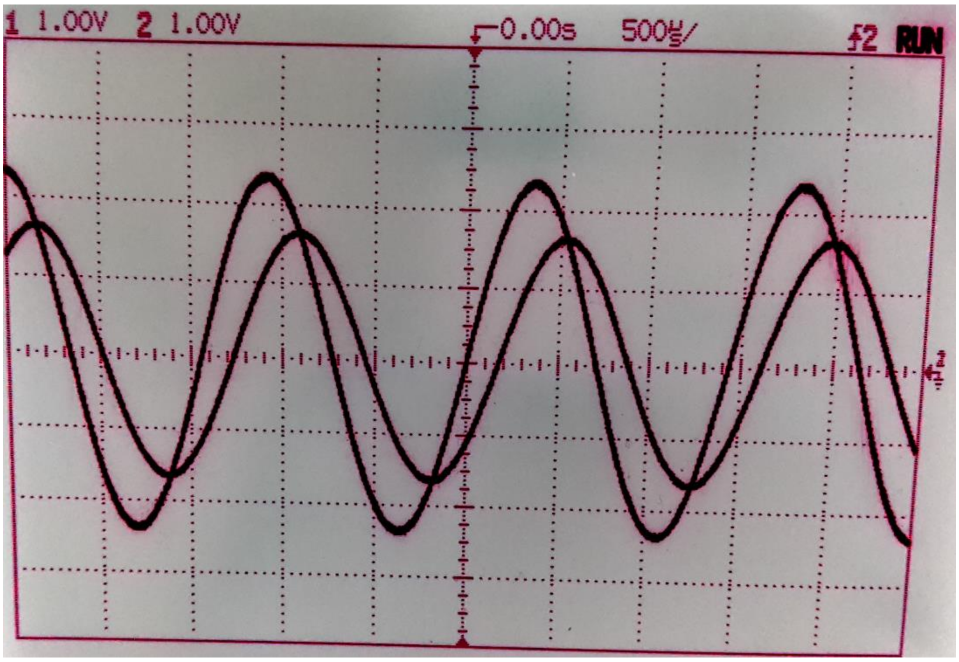

Figure 4.12 Output voltages with the parameters R_1 = 4.7kΩ, R_4 = R_8 = R_9 = 10kΩ and $C4$ = $C9$ = 22nF and frequency 700Hz.

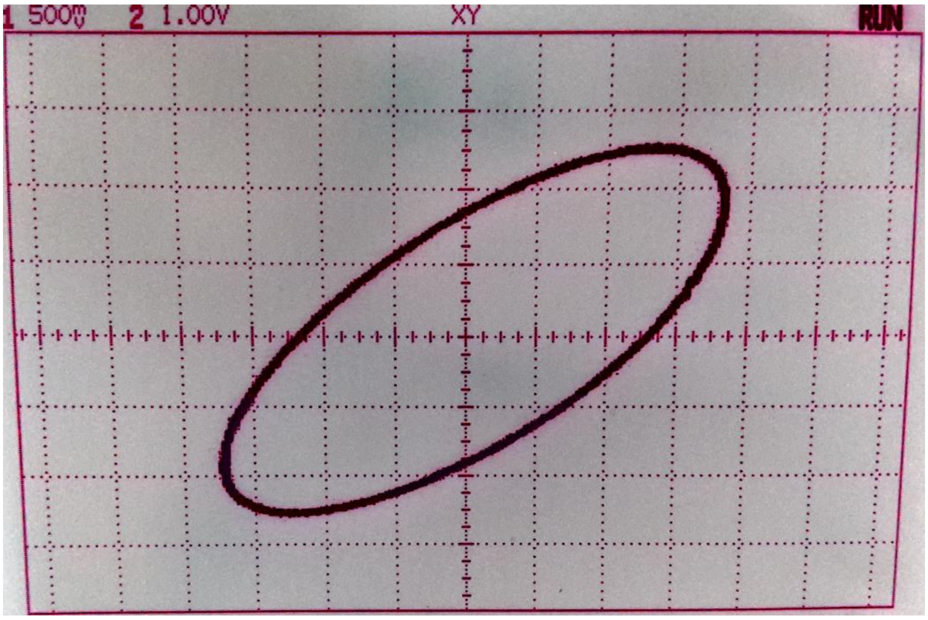

Figure 4.13 Shows the lissajous curve for this setup.

MCDBA

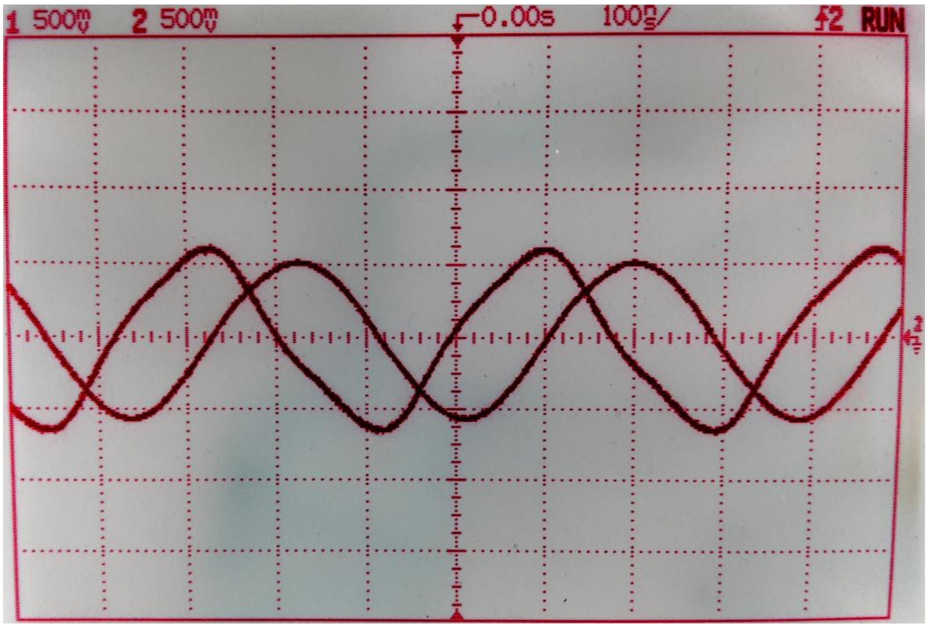

Figure 4.14 Output voltages with the parameters $R_1 = R_2 = 1k\Omega$ and $C1 = C2 = 12nF$ and frequency 2.6MHz.

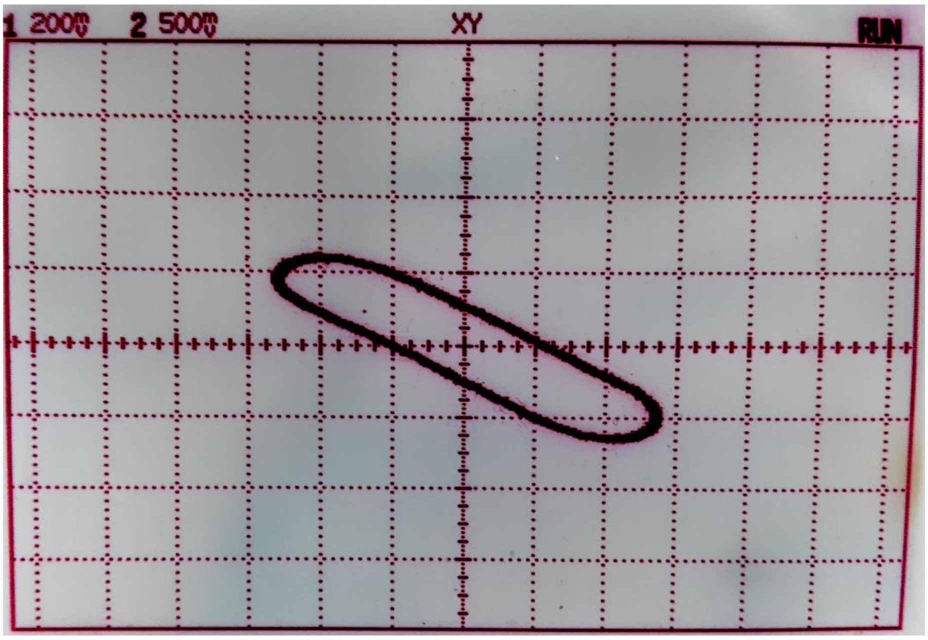

Figure 4.15 Shows the lissajous curve for this setup.

5. CONCLUSION

This thesis deals with active RC sinusoidal oscillator circuits. When the literature survey was carried out, many different active RC oscillator circuits were found, two of them was studied and simulation and experimental results were carried out.

The first considered circuit is the CFOA based active RC oscillator circuit proposed by Abuelma'ati in 2010 [39]. Experimental results and simulations of this circuit have been done in this thesis. It has been observed that the oscillator can operate below 1Hz at low frequencies and up to 9MHz at high frequencies. Since both, the operating frequency and oscillation condition are determined by resistances, the frequency can not be adjusted with single element.

The second considered circuit is the or orthogonal sinusoidal oscillator circuit proposed by Ayten in 2009 [39]. The circuit is implemented with MCDBA block. Experimental studies and analysis of this circuit has been carried out together with the design of the MCDBA element with the AD844 in this thesis. It has been observed that the oscillation can run below 1Hz at low frequencies and up to 2.6MHz at high frequencies. Frequency adjustment can be made at a certain frequency with a single resistance element.

Measured circuits created on breadboard showed expected behaviour and corresponded with Pspice simulation results for similar parameters.

From both oscillators design a PCB was made and measured for set frequencies. Those measurements showed lower amplitude levels than expected, especially for high frequency, this could be caused by the parts used in construction or PCB design. For this was the first experience of the author with oscillator construction, a minor design flaw is possible to occur.

However good experimental results were carried out and versatile features of modern active building blocks were presented and after minor updates, designed oscillators could find use in various practical applications.

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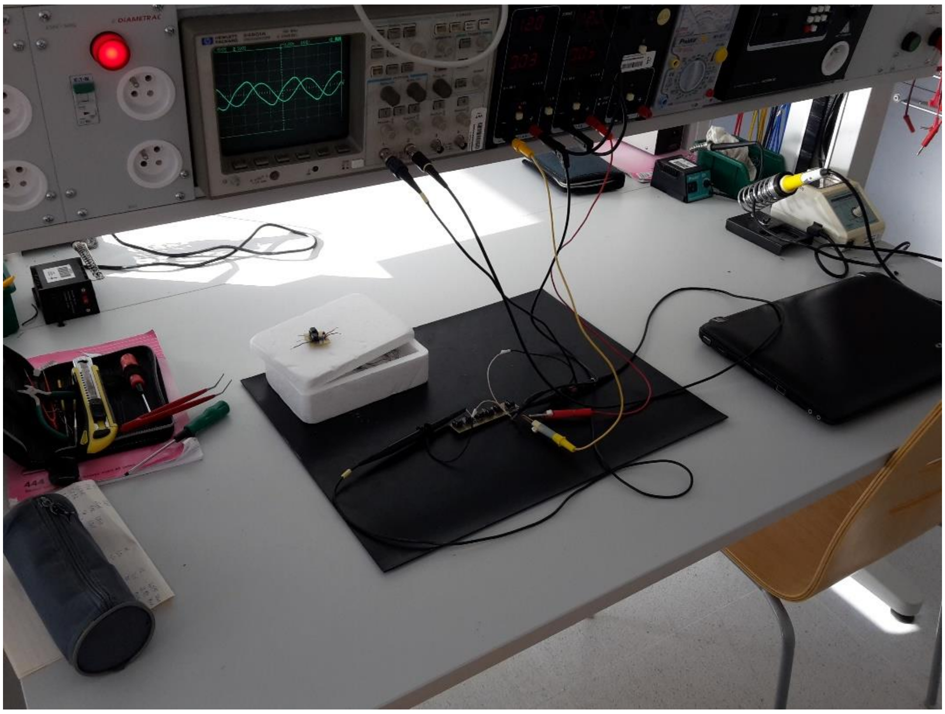
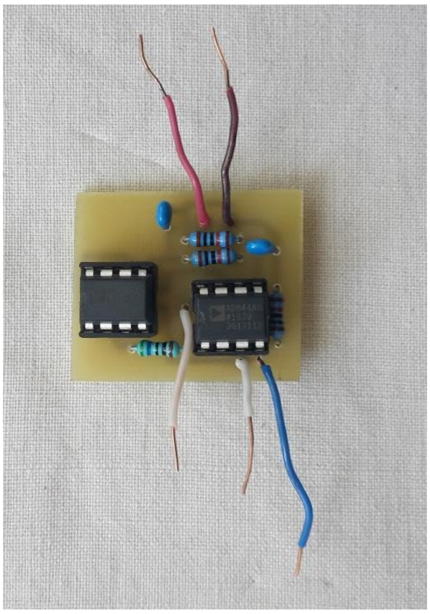
LIST OF ABBREVIATIONS

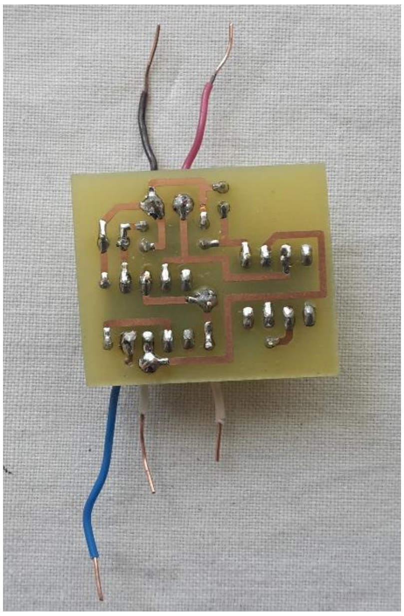
CFOA	Current feedback operational amplifier
PCB	Printed circuit board
FFT	Fast fourier transform
CC	Current conveyor
OTRA	Operational transresistance amplifier
CDBA	Current differencing buffered amplifier
FTFN	Four terminal floating nullor
OTA	Operational transconductance amplifier
CA	Current Amplifier
OPA	Operational Amplifier
VCO	Voltage controlled oscillator
CDTA	Current Differential Transconductance Amplifier
CCVS	Current Controlled Voltage Source

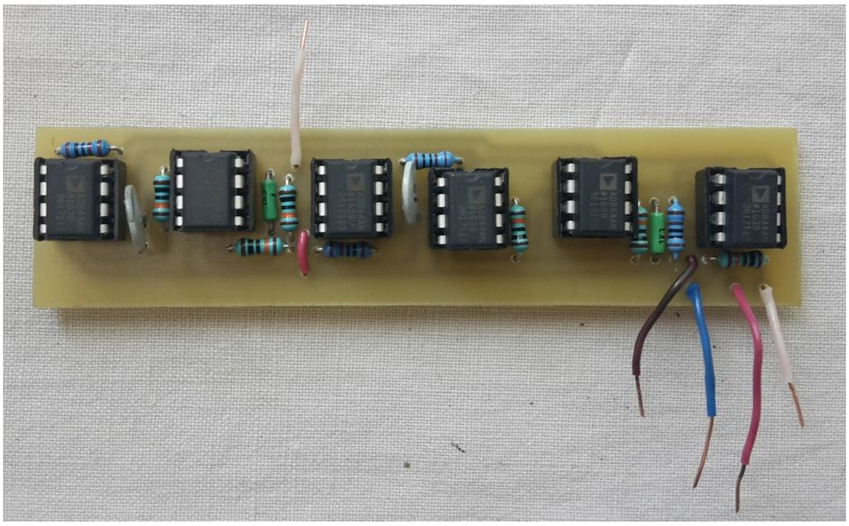
A CD With documentation, simulation profiles and PCB files

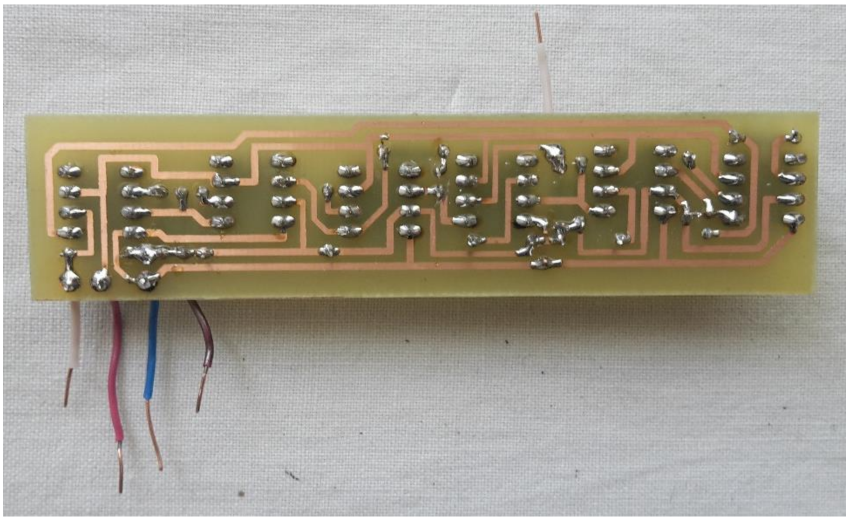
B Laboratory setup, created boards and breadboard

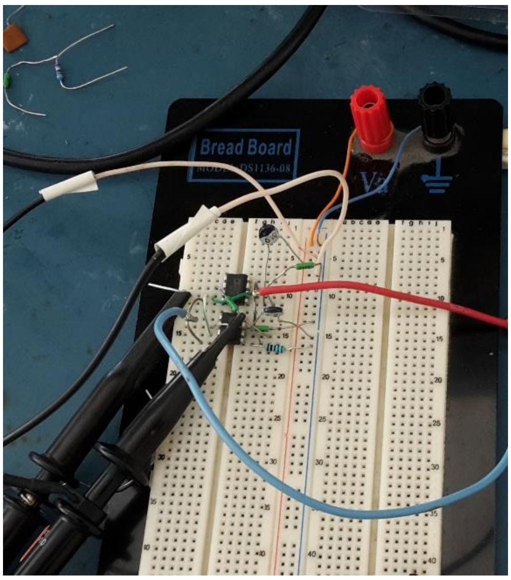








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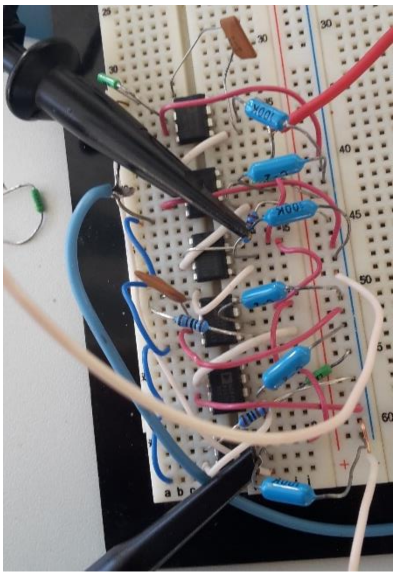
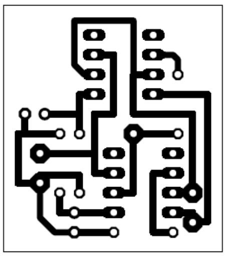
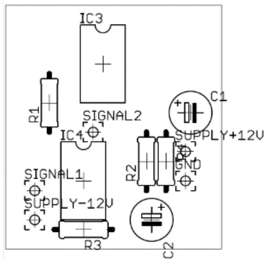


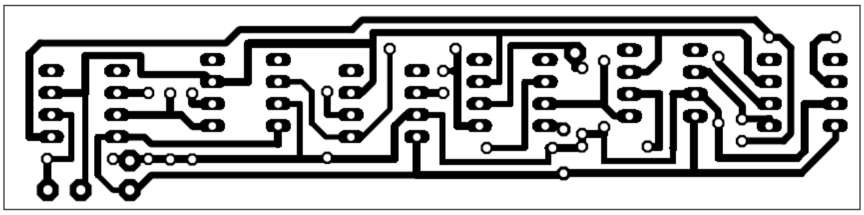
C PCB Plans

Dimensions: 28x32mm

Parts placement







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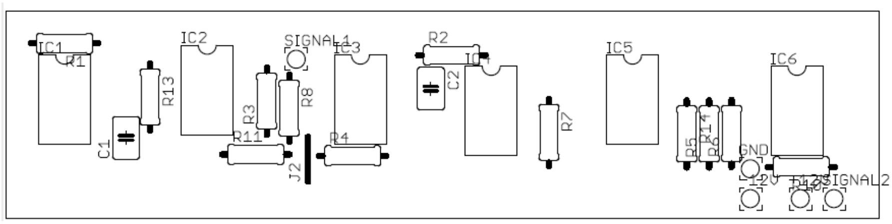

Parts placement